THE IMPACT OF PHOTOVOLTAIC POWER PLANT PENETRATION LEVEL ON SECURITY CONSTRAINED UNIT COMMITMENT AND AN APPROACH FOR REDUCING CURTAILMENT OF PV ENERGY

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ABSTRACT

THE IMPACT OF PHOTOVOLTAIC POWER PLANT PENETRATION LEVEL ON SECURITY CONSTRAINED UNIT COMMITMENT AND AN APPROACH FOR REDUCING CURTAILMENT OF PV ENERGY

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As a main rule of electricity grid, the balance of generation and demand must be maintained. The system operators execute "Unit Commitment (UC)" process in day-ahead market in order to fulfill this aim. The Security Constrained Unit Commitment (SCUC) algorithm creates optimal hourly schedules for generators with minimum total electricity generation cost considering the forecasted hourly demands for the next day and the generation offers while satisfying the constraints of generators and transmission system.

In this thesis, SCUC considering PV power plants is studied. The increasing number of PV power plants and governmental regulations targeting 20% and above Renewable Energy Sources (RES) share of the total energy urge the analysis of the impact of large capacities of RES to electricity market and generation cost. Taking this as the main motivation, the SCUC algorithm is modified and applied on the IEEE 118 Bus Test System. The capacity of PV power plants and connection buses are determined using references from the literature, and the test system is modified by placing these plants to the relevant buses. Average and intermittent daily PV generation values are generated using the past solar irradiation measurements. The capacity and number of PV power plants are increased systematically. The SCUC algorithm is modified by adding PV characteristics and Curtailment Penalty Price (CPP), and the CPP impact on reducing curtailment of available PV energy is analyzed in a systematical way.

The effect of large capacities of PV generation to the total electricity generation cost is evaluated by inspecting the committed PV generation and resulting curtailment of available PV energy through the case studies. Moreover, a method for reducing curtailment that increases the utilization of PV generation is introduced and the applicability is verified.

Keywords: Security Constrained Unit Commitment (SCUC), PV Power Plants, Curtailment Penalty Price (CPP), Day-Ahead Market, Curtailment Compensation, High PV Penetration.

ÖZ

FOTOVOLTAİK ELEKTRİK SANTRAL YAYGINLIĞININ GÜVENLİK KISITLI ÜNİTE DEVREYE ALMA ÜZERİNDEKİ ETKİSİ VE FOTOVOLTAİK ENERJİ SINIRLANDIRILMASINI AZALTMAK İÇİN BİR YAKLAŞIM

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Elektrik şebekesinin bir ana kuralı olarak üretim ve tüketim dengesi her zaman korunmalıdır. Sistem işletmecisi gün öncesi piyasasında "Ünite Planlama/ Devreye Alma" sürecini uygulayarak toplam üretim ve tüketim dengesini sağlar. Güvenlik Kısıtlı Ünite Devreye Alma (SCUC) algoritması, bir sonraki güne ait saatlik yük tahmin bilgisi ile üretici şirketlerin saatlik üretim tekliflerini kullanarak ve jeneratör ile iletim sistemi kısıtlarını göz önüne alarak, toplam yükü minimum elektrik üretim fiyatı ile karşılayan jeneratörler için en uygun saatlik üretim/devreye alma planını oluşturur.

Bu tez çalışmasında, SCUC algoritması fotovoltaik (FV) elektrik santralleri dâhil edilerek incelenmiştir. Giderek artan sayıda FV elektrik santrallerinin devreye alınması ve toplam enerjide yenilenebilir enerji kaynaklarının payının %20 ve üzerinde olacak şekilde planlanması, yüksek kapasiteli yenilenebilir enerji kaynaklarının elektrik piyasası ve üretim maliyeti üzerindeki etkisinin incelenmesini gerektirmiştir. Bu gereklilik FV elektrik santral modelinin SCUC'ye dâhil edilmesindeki ana motivasyondur. SCUC algoritmasına ekleme yapılarak IEEE 118 Bara Test Sistemi üzerine uygulanmıştır. Literatürdeki referanslar kullanılarak FV elektrik santral kapasiteleri ve bağlantı baraları belirlenmiş ve test sistemi bu FV santrallerinin ilgili baralara bağlanmasıyla değiştirilmiştir. 24 saatlik ortalama ve kesikli FV üretim verisi geçmiş aydınlanma ölçüm verilerinden yararlanılarak oluşturulmuştur. FV santral kapasite ve sayısı sistematik bir şekilde artırılmıştır. Standart SCUC algoritmasına FV karakteristiği ve "Sınırlandırılma Ceza Bedeli" eklenerek ünite planlaması ve toplam elektrik üretim maliyeti üzerindeki etkisi sistematik bir biçimde incelenmiştir.

Bu çalışmalar sonucunda yüksek kapasiteli FV elektrik santrallerinin devreye alınan jeneratörler ve üretim miktarları ile toplam elektrik üretim maliyeti üzerindeki etkisi analiz edilmiştir. Ayrıca devreye alınan ve sınırlandırılan FV üretim miktarları incelenerek yüksek kapasiteli FV elektrik santrallerinin kullanım oranı değerlendirilmiştir. Bunun yanısıra FV elektrik santrallerinin üretim sınırlandırılmasını azaltarak FV enerji kullanım oranını artıran bir yöntem üzerinde çalışılmış ve uygulanabilir olduğu gösterilmiştir.

Anahtar Kelimeler: Güvenlik Kısıtlı Ünite Devreye Alma, FV Elektrik Santralleri, Sınırlandırılma Ceza Bedeli, Gün Öncesi Piyasası, Sınırlandırılma Kompanzasyonu, Yüksek FV Penetrasyonu.

To My Beloved Family

&

And My Dearest Love

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CHAPTER 1

INTRODUCTION

Global electricity generation has increased from 14,000 TWh to 16,000 TWh from 1997 to 2002, 16,000 TWh to 19,900 TWh from 2002 to 2007, and it became 22,600 TWh in 2012 [1]. If the impact of 2008 financial crisis is not considered, exponential growth is achieved in electrical energy consumption that brings the necessity of proper electricity generation, transmission and distribution investments and operation planning techniques in order to maintain the generation and demand balance.

The tendency towards Renewable Energy Sources (RES) has considerably increased due to increasing energy demand, diminishing fossil fuels and their carbon emissions leading adverse environmental impact. This interest leads the renewable energy investment in both low voltage side as distributed generation and transmission side with large capacities of RES integration. This fact leads energy authorities to make regulations for increasing the RES ratio in total installed capacity such as the California and the European Union (EU) examples. In California, the RES ratio in total installed capacity is targeted to reach 33%, and also the EU-28 countries have a target of reaching 20% of RES in the Gross Final Energy Consumption (GFEC) ratio by 2020 [2][3]. (The GFEC is defined as the ratio of RES in any energy required process such as transportation, air and water heating /cooling and so on.)

Solar energy, wind energy, hydropower, biomass, geothermal and wave energy are the types of RES. The electricity obtained from RES exhibits intermittency and volatility due to the unpredictable behavior of natural resources. Therefore, the RES power plants in electrical grid deviate from any other conventional thermal or nuclear power plants due to the risk of unpredictable unavailability that might result with unstable operation of electrical grid since the large amount of unplanned loss in generation might not be compensated because of limited system reserves.

The deregulated energy market is composed of a number of entities such as Generation Companies (GENCOs) which are responsible of generation of electricity; Distribution Companies (DISCOs) which are responsible of operation of maintenance and operation of distribution systems; and the Independent System Operator (ISO). The ISO is the entity that is responsible of balancing total generation and demand in electricity markets. The task of maintaining generation and demand balance of electrical grid from one-day ahead is called Unit Commitment (UC). The UC process is an optimization algorithm that has an objective function that minimizes the total operating and no load costs of generators while satisfying the technical constraints of generators and generation-demand balance. This process is a crucial part of any electrical grid acting as not only the balancing mechanism of the electrical grid but also being a market where the commodity of electricity is sold and the market is cleared.

The increasing interest in RES requires the integration of RES into the UC algorithm which results a state of the art topic for UC researches. The two main concerns that exist for RES integration are modeling the intermittency and varying behavior of RES, and the effect of large RES capacities.

The state of the art UC method in literature and industrial appliances is Security Constrained Unit Commitment (SCUC) that finds the optimal generator schedule with minimum total electricity generation cost considering the constraints of generators and transmission system. The difference of SCUC from conventional UC is that it considers the transmission network limitations while determining the on/off states of generating units and power outputs.

The inclusion of RES in the SCUC algorithm brings two main questions:

- Will there be any curtailment from the available renewable energy generation?
- Under the occurrence of such a curtailment, how will it be managed in electricity market?

As the RES capacity increases, the intermittency can cause system instability because of the technical constraints of generators and transmission system, and this leads curtailment of available RES energy [4], [5], [6]. The curtailment leads undesired operation of RES which means that the GENCO employing RES electricity generation facilities limits its generation even there is excess of electrical energy that could be injected to the grid. Therefore, this situation reduces the income of RES companies and acts as an obstacle against the renewable energy ratio targets.

Current studies of SCUC considering RES are focused on developing a robust SCUC algorithm which includes wind power characteristics and variable load, and give optimal schedule for generators with minimal cost [4], [5] ,[7], [8]. The impact of different size of wind capacity (including 40% wind capacity over total) on SCUC, wind curtailment, total generation cost and reserve requirements are also examined in [8]. The reason is explicit since the most available intermittent type of RES in the USA is the wind energy (hydropower and biomass are excluded) [9], and a number of ISOs utilize the SCUC algorithm in order to find the optimal day-ahead schedule [10], [11], [12], [13]. The installed capacity of wind power in the USA is the second greatest in the world by 2014 with having 65 GWp installed capacity after 114 GWp installed capacity of China [14].

It is claimed that the solar energy including Photovoltaics (PV), Concentrated PV (CPV) and Concentrated Solar Power (CSP) will be the world's largest source of electricity by reaching 4,600 GW total installed capacity by 2050 [15]. The total installed capacity of solar power is 181 GW by 2014 [16], and the total installed capacity of electricity is about 5,550 GW by 2012 with a yearly increment rate of 200 GW [17]. If this yearly increment rate is assumed to be the same for the following years, the total installed capacity of electricity is expected to become 13,150 GW by 2050.

The PV energy has the most interest among the solar energy types [18]. The daily electricity generation characteristics of PV energy is different from wind energy since the PV energy is not available for 24 hours. In addition, the output of PV energy is more dynamic because it is more dependent on environmental conditions compared to wind. For example, shading effects, irradiation amount, ambient temperature and dusts are the main parameters that effect PV generation amount. Therefore, the results of the SCUC analyses including wind cannot be used for PV power plants.

In this thesis study, the effects of large PV power plants and the intermittent characteristics of PV power to the SCUC is evaluated by integrating the PV power characteristics to the SCUC algorithm with varying number and size of PV power plants. In addition, Curtailment Penalty Price (CPP) is introduced and added to the SCUC algorithm, and its impact on reducing the curtailment of PV energy is evaluated. A modular and parametric SCUC algorithm is developed in MATLAB and tested on the IEEE 118 Bus Test System. The technical parameters of transmission network and generators are taken from the IEEE model. The 24 hours PV generation data is created by using the System Advisor Model (SAM) software from the National Renewable Energy Laboratory (NREL). 529 SCUC problem files containing the IEEE 118 Bus Test System with different number and size of PV power plants are created in MATLAB. These 529 problem files are created for seven tests each of which includes two scenarios under two cases. The problem files are solved by using IBM CPLEX Optimization software and the resulting data is examined considering the listed perspectives below:

- The effect of PV power plants' installed capacity on

  - The standard 24 hours SCUC and total daily electricity generation cost, and
  - The curtailed PV energy are examined.

- The curtailment penalty price is added to the SCUC algorithm and its effect on

  - The reduction of PV curtailment, and
  - The total daily electricity generation cost are examined.

- The two scenarios run for the two cases:

  - The IEEE 118 Bus Test System with PV power plants having average data for 24 hours PV generations,
  - The IEEE 118 Bus Test System with PV power plants having intermittent data for 24 hours PV generations.

As a result, with the help of these analyses, the relation between the curtailed energy and the size of PV power plants are examined. In addition, the impact of curtailment penalty price on the reduction of PV curtailment is examined which can enable higher capacities of PV power plants to be connected to the grid and paves the way for achievement of the targeted RES penetration.

In Chapter 2, the growth of renewable energy sources and roadmaps of future electricity generation are given. Firstly, the penetration levels of RES in leading countries are presented. Secondly, corresponding to the penetration levels, the roadmaps of future electricity generation in these countries are provided. After that, the types of RES are introduced. The PV type of RES is explained in detail, the characteristics of PV generation and creation of daily PV generation data which is used in case studies are presented.

In Chapter 3, the constraints of generators and transmission system that are used in developing the SCUC algorithm are given. The usage of the constraints and the objective function of the algorithm is explained in detail. The curtailment term is defined in the scope of SCUC constraints. The literature review about current studies and the applications of SCUC including RES are provided. The usage of SCUC including RES in day-ahead market is explained. The current experiences and practices of RES curtailments are provided. The integration of PV power plants and curtailment penalty price into the SCUC algorithm are given. The standard and modified SCUC problems are summarized.

In Chapter 4, the simulations and the results are given. The IEEE 118 Bus Test System and the relevant data are introduced. The case studies including seven tests for both of the two cases including two scenarios each are given. The software environment including MATLAB and IBM CPLEX Optimization Software is explained. The relations between the percentages of curtailment reduction and cost increment between two scenarios in each case and in each test are provided.

In Chapter 5, the results are summarized. The benefits of the proposed curtailment penalty price integration into the SCUC algorithm for reducing the curtailment of available PV energy are explained. The future works that can be done for enhancing the simulated tests and proposed CPP integration, and possibilities of industrial usage areas are presented.

In Appendix, summary of the SCUC algorithm is provided.

CHAPTER 2

GROWTH OF RENEWABLE ENERGY SOURCES AND ROADMAPS OF FUTURE ELECTRICITY GENERATION

2.1 Penetration Levels of Renewable Energy Sources

Recalling that the interest in the renewable energy sources is increasing because of the carbon emission concerns and the decreasing fossil fuels, energy authorities of countries around the world give incentives for enabling higher capacities of Renewable Energy Sources (RES) to be connected to the grid, and consequently the RES ratio over conventional generators is increasing.

According to the latest data on Eurostat website, the share of renewable energy in electricity by country is increasing cumulatively by year. In addition, the total share of RES in electricity for the whole European Union (EU) is given as 25.4% by 2013 as given in Table 2.1. This increasing trend is not only the result of the incentives for RES but also due to the endorsements from European Union's energy policy and energy authorities.

There is another measure of total energy share of RES in total energy demand which is used for measuring the contribution to the 2020 objectives on renewable energy for the EU and named as "Gross Final Renewable Energy Consumption (GFREC)". It is the measure of amount of renewable energy consumed for not only electricity but also heating and cooling, and transportation. The GFREC term is also expressed as a RES share against the gross final energy consumption and given in Table 2.2.

Table 2.1 Share of renewable energy (percentage) in electricity by country [19].

GEO/TIME	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*
European Union (28 countries)	14.3	14.8	15.3	16.1	17.0	19.0	19.6	21.7	23.5	25.4
Belgium	1.7	2.4	3.1	3.6	4.6	6.2	7.1	9.1	11.3	12.3
Bulgaria	9.1	9.3	9.3	9.4	10.0	11.3	12.7	12.9	15.8	18.9
Czech Republic	3.6	3.7	4.0	4.6	5.2	6.4	7.5	10.6	11.6	12.8
Denmark	23.8	24.7	24.0	25.0	25.9	28.3	32.7	35.9	38.7	43.1
Germany	9.4	10.5	11.8	13.6	15.1	17.4	18.1	20.9	23.6	25.6
Estonia	0.6	1.1	1.5	1.5	2.1	6.1	10.4	12.3	15.8	13.0
Ireland	6.0	7.2	8.7	10.4	11.2	13.4	14.5	17.3	19.5	20.9
Greece	7.8	8.2	8.9	9.3	9.6	11.0	12.3	13.8	16.4	21.2
Spain	19.0	19.1	20.0	21.7	23.7	27.8	29.8	31.6	33.5	36.4
France	13.8	13.8	14.1	14.4	14.3	15.0	14.7	16.2	16.4	16.9
Croatia	32.5	32.8	32.2	30.9	30.8	32.6	34.2	34.2	35.5	38.7
Italy	16.1	16.3	15.9	16.0	16.6	18.8	20.1	23.5	27.4	31.3
Cyprus	0.0	0.0	0.0	0.1	0.3	0.6	1.4	3.4	4.9	6.6
Latvia	46.0	43.0	40.4	38.6	38.7	41.9	42.1	44.7	44.9	48.8
Lithuania	3.6	3.8	4.0	4.7	4.9	5.9	7.4	9.0	10.9	13.1
Luxembourg	2.8	3.2	3.2	3.3	3.6	4.1	3.8	4.1	4.6	5.3
Hungary	2.2	4.4	3.5	4.2	5.3	7.0	7.1	6.4	6.1	6.6
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6	1.0	1.6
Netherlands	4.4	6.3	6.6	6.0	7.5	9.1	9.7	9.8	10.5	10.1
Austria	61.9	62.4	62.4	64.6	65.2	67.8	65.7	66.0	66.5	68.1
Poland	2.1	2.7	3.0	3.5	4.4	5.8	6.6	8.2	10.7	10.7
Portugal	27.5	27.7	29.3	32.3	34.1	37.6	40.7	45.9	47.6	49.2
Romania	28.4	28.8	28.1	28.1	28.1	30.9	30.4	31.1	33.6	37.5
Slovenia	29.3	28.7	28.2	27.7	30.0	33.8	32.1	30.8	31.4	32.8
Slovakia	12.4	13.5	15.1	15.7	16.7	17.8	17.8	19.3	20.1	20.8
Finland	26.7	26.9	26.4	25.5	27.3	27.3	27.6	29.4	29.5	31.1
Sweden	51.2	50.9	51.8	53.2	53.6	58.3	56.0	59.9	60.0	61.8
United Kingdom	3.5	4.1	4.5	4.8	5.5	6.7	7.4	8.8	10.8	13.9

Table 2.2 Share of renewable energy (percentage) in gross final energy consumption in European Union [19].

	2004	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*
European Union (28 countries)	8.3	8.7	9.2	10.0	10.5	11.9	12.5	12.9	14.3	15.0

The RES term used in the above tables stands for the total of all types of renewable generation such as solar power, wind power, hydropower, biomass, biogas and geothermal.

It is seen from Table 2.2 that the total share of renewable energy in gross final energy consumption is 15% by 2013. However, the EU energy policy requires this ratio to increase 20% by 2020 [2]. In other words, every country in EU has its own target for achieving 20% ratio at total. The ratios for each individual country and the total are given Figure 2.1.

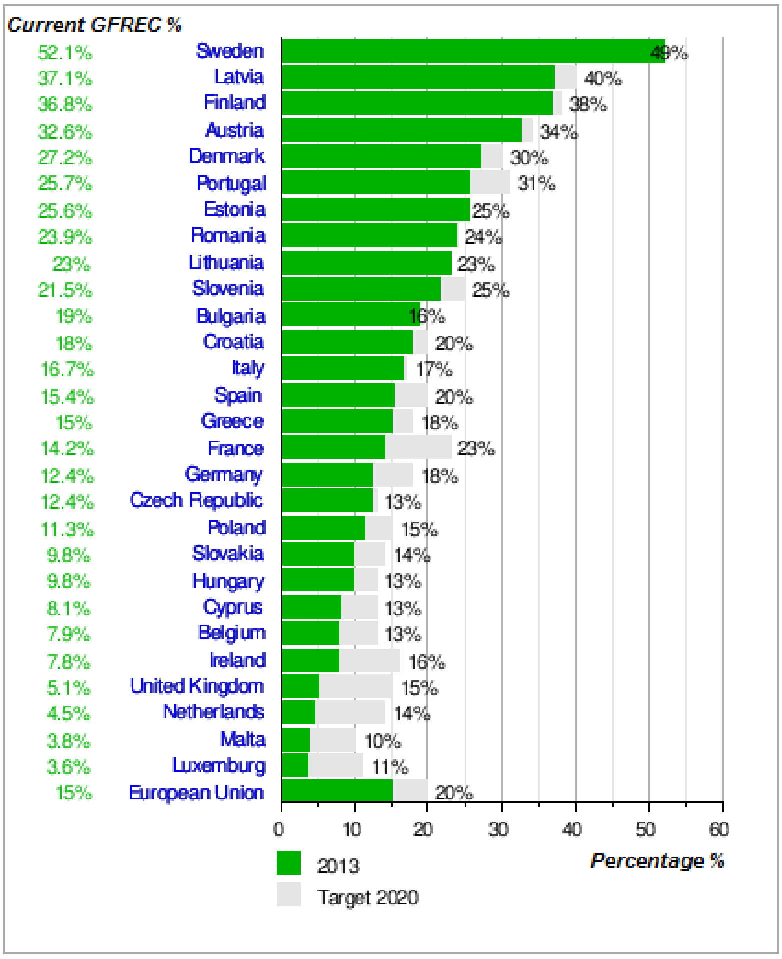

Figure 2.1 Share of renewable energies in gross final energy consumption in EU-28 countries in 2013 [2].

In California, according to the California Public Utilities Commission regulation, the procurement from eligible renewable energy sources in the area of California ISO responsibility is to be 33% by 2020, which is now around 23% [3].

Many countries across the world have targets of RES share of consumed electricity for future years and the complete list is given in [16].

2.2 Types of Renewable Energy Sources and the Portfolio in the World

The total installed capacity of RES is reached 1,712 GW including 1,055 GW hydropower. The RES capacities in the World, EU Countries, the BRICS (Brasilia, Russia, India, China, South Africa) and the top seven countries by 2014 are given in Figure 2.2. (Figure 2.2 is taken from open source material which is available at *Renewable Energy Policy Network for 21st* – REN21 website.)

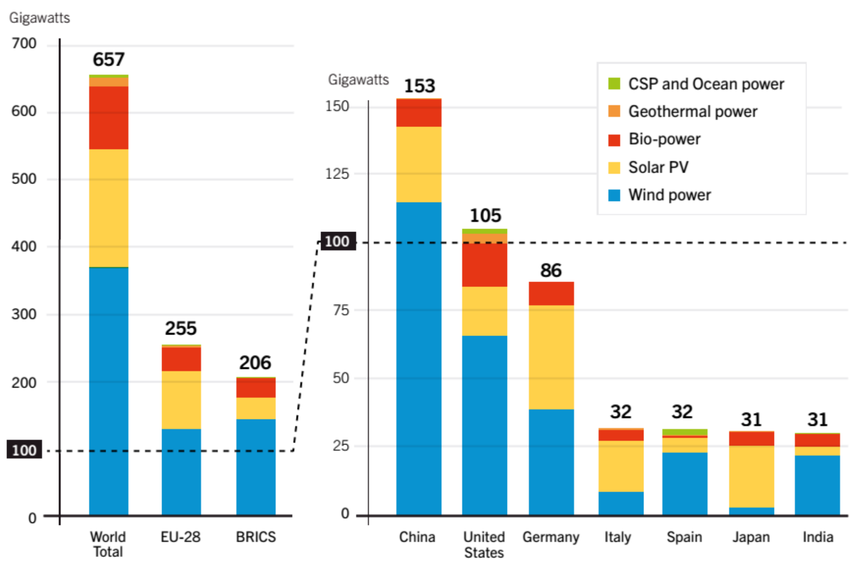

Figure 2.2 RES capacities in the World, EU-28, BRICS and the top seven countries [19].

The total RES capacities of each type in the World, EU, BRICS and the top seven countries including hydropower is given in Table 2.3.

Table 2.3 The total RES capacity in the World, EU, BRICS and the top seven countries including hydropower, 2014 [16].

	World	EU	BRICS	China	United States	Germany	Italy	Spain	Japan	India
TECHNOLOGY	**Capacity (GW)**			**Capacity (GW)**						
Bio Power	93	36	29	10	16.1	8.8	4	1	4.7	5
Geothermal Power	12.8	1	0.1	0	3.5	0	0.9	0	0.5	0
Hydropower	1,055	124	463	280	79	5.6	18	17.3	22	45
Ocean Power	0.5	0.2	0	0	0	0	0	0	0	0
Solar PV	177	87	32	28	18	38	18.5	5.4	23	3.2
Concentrated Solar Thermal Power (CSP)	4.4	2.3	0.2	0	1.6	0	0	2.3	0	0.2
Wind Power	370	129	144	115	66	39	8.7	23	2.8	22
Total Renewable Power Capacity (Hydropower is Included)	1,712	380	668	433	185	92	50	49	54	76
Total Renewable Power Capacity (Hydropower is not Included)	657	255	206	153	105	86	32	32	31	31

The characteristics of the RES types are differing from each other by generation hours in a day. For instance the solar generation is only available when the sun is shining while the wind power can be available at any hour. In order to express the situation in detail, an example hourly generation scheme of electricity by type is given in Figure 2.3 which interprets the current power plants and their generation values in the area of California ISO. (Figure 2.3 is taken from open source material which is available at *California ISO* website.)

24-Hour Renewables Production

Renewable Resources	Peak Production Time	Peak Production (MW)	Daily Production (MWh)
Solar Thermal	11:03	651	5,883
Solar	11:00	5,348	49,297
Wind	23:09	3,193	36,549
Small Hydro	19:12	239	3,570
Biogas	5:50	167	3,842
Biomass	6:04	280	6,337
Geothermal	1:51	1,055	24,315
Total Renewables			**129,793**
Total 24-Hour System Demand (MWh):			*598,538*

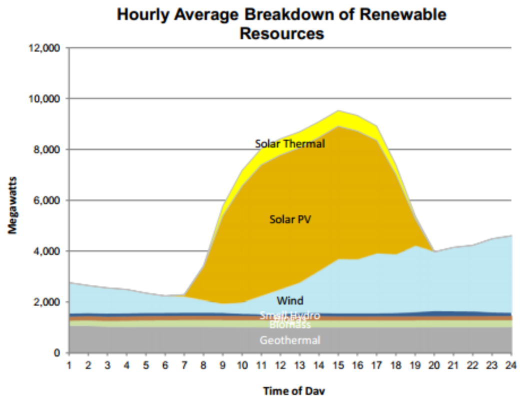

Figure 2.3 24 Hour renewables production in California ISO area [20].

2.3 Types of Solar Energy to Electrical Energy Conversion

There are three types of generating electrical energy from sun, namely, Photovoltaics (PV), Concentrated Solar Thermal Power (CSP), and Concentrated Photovoltaics (CPV).

2.3.1 Photovoltaics (PV)

The Photovoltaics type uses solar cells which converts the incoming solar energy from sunlight to direct current.

The PV generation has the most interest in generating electricity from solar energy, and its marginal cost per kWh is decreasing by year as shown in Figure 2.4.

The PV energy sources have growing interest and spreading with an increasing rate which are given by cumulative capacity between the years 2006 and 2014 for regions across the world as shown in Figure 2.5. (Figure 2.5 is taken from open source material which is available at *European Photovoltaic Industry Association – EPIA* website.)

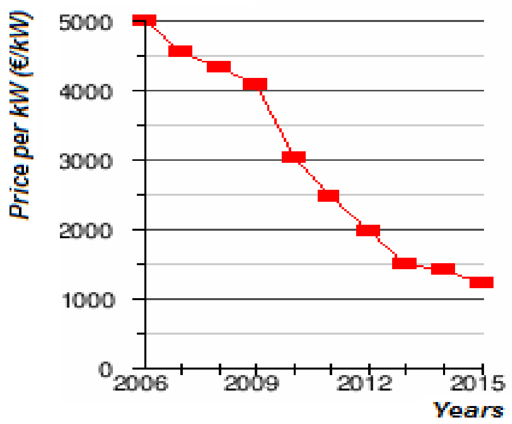

Figure 2.4 Rooftop PV prices in Germany (€/kW) [21].

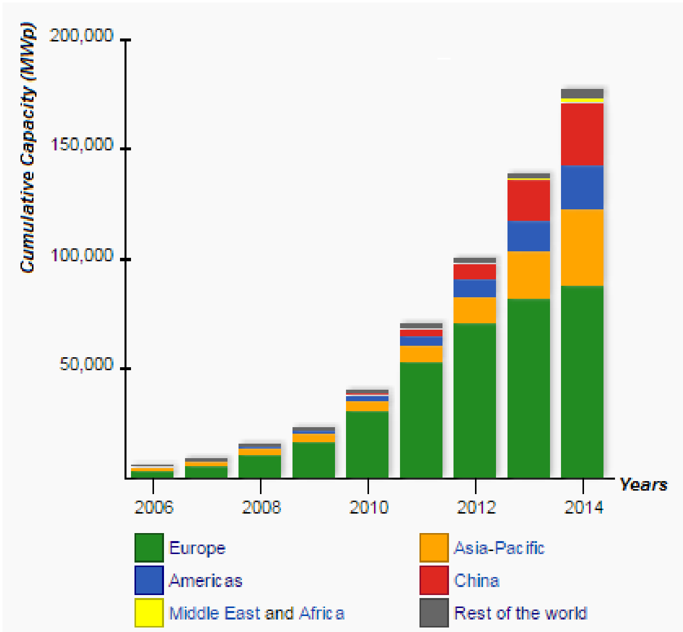

Figure 2.5 Cumulative PV capacity (MWp) grouped by region [22].

In 2015, between 50 and 57 GW power of PV is forecasted to be deployed around the world and the installed capacity of PV is projected to expand to 500 GW until 2020 (Totally 142 GW in 2013, 177 GW in 2014). It is claimed that by 2050, solar power including concentrated solar thermal power and concentrated photovoltaics will become the largest source of electricity. The total PV capacity is expected to become 4,600 GW, and most of this capacity is forecasted to be installed in India and China [15].

The list of ten countries having the worldwide highest PV installation capacities by 2014 is given in Table 2.4.

Table 2.4 Top 10 total PV capacities by country (GWp) [23].

Order	Country	Total Capacity (GW)
1	Germany	38.20
2	China	28.20
3	Japan	23.30
4	Italy	18.46
5	United States	18.28
6	France	5.66
7	Spain	5.36
8	United Kingdom	5.10
9	Australia	4.14
10	Belgium	3.07

The world's largest PV station is "Solar Star" which has 579 MWp total capacity. The PV station was brought online by June 19, 2015 and located at Antelope Valley, California. The next largest PV stations are "Topaz Solar Farm" and "Desert Sunlight Solar Farm" which are also located in California and each of them has 550 MWp total capacity [24].

In Turkey, there are totally 273 PV power plants, and the total capacity is 175 MW which are connected to electrical grid from distribution side and named as Distributed Energy Resources (DERs) [25]. There are projected and approved utility scale PV power plant projects which will have 1.25 GW total capacity by the end of 2016 [25]. According to the future energy roadmap of Turkey defined by the Planning Council under Ministry of Development, the RES share in total energy generation is planned to exceed 30% by 2023 [26], [27]. In December 2014, the Ministry of Energy and Natural Resources issued a new national renewable energy action plan which aims to increase the country's renewable energy generation capacity to 61 GW by 2023 (34 GW in the form of hydro, 20 GW in the form of wind, 5 GW in the form of solar generation, 1 GW in the form of geothermal, and 1 GW in the form of biomass) [27].

2.3.2 Concentrated Solar Thermal Power (CSP)

The CSP type of solar energy systems use mirrors and/or lenses to intensify sunlight to small area and create heat which drives a steam engine connected to electrical power generator.

The portion of CSP systems in electricity generation from solar power is low compared to PV, and the total worldwide CSP capacity is 4.4 GW.

The list of top five countries with the highest worldwide installed CSP capacities in 2013 is given in Table 2.5.

Table 2.5 National CSP capacities (MWp) [11].

Order	Country	Total Capacity (MW)	Added Capacity in 2013 (MW)
1	Spain	2,300	350
2	United States	882	375
3	United Arab Emirates	100	100
4	India	50	50
5	Algeria	25	0

2.3.3 Concentrated Photovoltaics (CPV)

As another method of producing electricity from sun is Concentrated Photovoltaics which uses lenses and curved mirrors similar to CSP systems, but CPV utilizes this intensified sunlight by highly efficient PV cells, and this type of solar panels generally use two axes sun trackers with cooling systems [15].

Despite the fact that the CPV is more efficient compared to standard PV, it has some disadvantages listed as [28]:

- Lack of utilizing diffuse radiation,
- Requirement of sun tracking with precision,
- Requirement of cleaning more,
- Cannot be installed on rooftops because of the size, and
- More investment cost requirement compared to standard PV.

The capacity of the largest CPV power plant is 80 MWp and located in Golmud, China. The worldwide total capacity is about 330 MWp [28].

It is observed from Tables 2.4, 2.5 and reference [28] that the CSP has more interest compared to CPV, and the PV is the most frequent one.

2.4 Characteristics of PV Generation and Creation of Daily PV Generation Data

Characteristics of PV generation mainly depends on solar irradiation and ambient temperature. However, the effect of ambient temperature on the output generation of PV panels is relatively low compared to solar irradiation. This situation enables making estimation of output generation of PV panels using solar irradiation values.

The labelled output generation values of PV panels are given for the maximum irradiance value, which is 1,000 W/m^2. Therefore, if the hourly irradiation data of the corresponding place is known, then the hourly output generation of the PV panel is determined by multiplying the labelled PV capacity of PV panel and the linear ratio obtained by dividing the estimated irradiation value by 1000.

In this section, the characteristics of daily PV generation is expressed by giving example daily generation scheme, and the creation of daily PV generation data which is used in the case studies is explained.

In order to have realistic 24 hours PV generation data, an example monthly average PV generation data for 24 hours is used. The selected data belongs to Los Angeles – California which is taken from System Advisor Model (SAM) software provided by National Renewable Energy Laboratory (NREL) in the USA. The monthly average data taken from NREL is given in Figure 2.6.

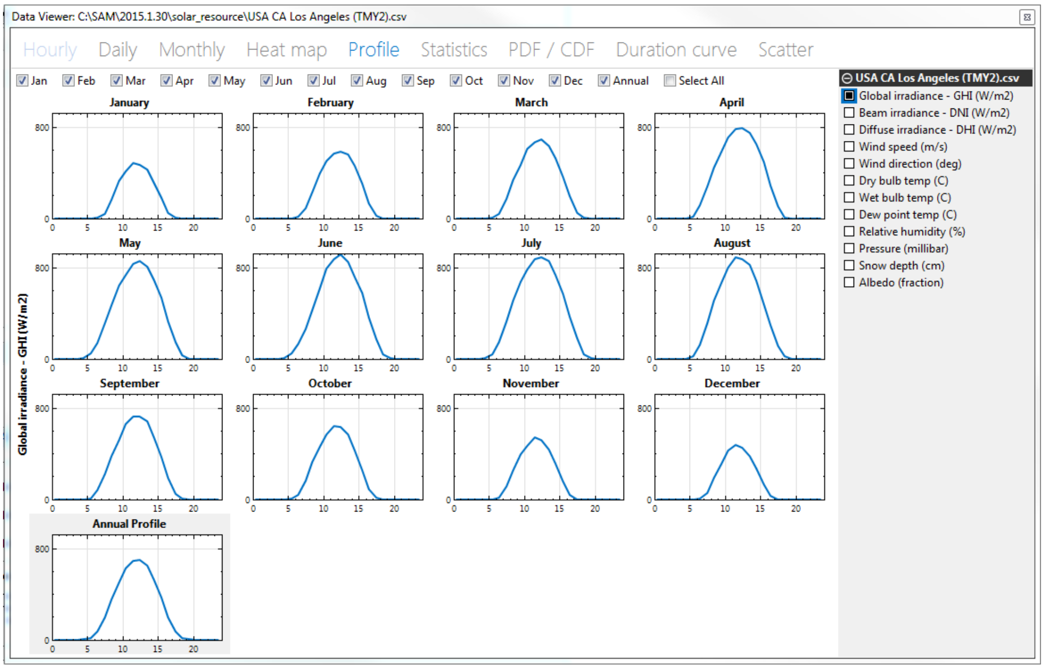

Figure 2.6 Monthly average global irradiance values for Los Angeles – California.

The 24 hours average irradiation amounts and the hourly generation values of an example 50 MW PV power plant data are given in Tables 2.6 and 2.7, respectively.

Table 2.6 Monthly average irradiance values for 24 hours (W/m^2).

H.	*JAN.*	*FEB.*	*MAR.*	*APR.*	*MAY.*	*JUN.*	*JUL.*	*AUG.*	*SEP.*	*OCT.*	*NOV.*	*DEC.*	*ANNUAL*
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	2	0	0	0	0	0	0	0
6	0	0	1	12	42	45	37	23	8	1	0	0	14
7	0	9	41	110	141	128	149	122	77	38	16	2	69
8	41	88	169	277	313	262	329	308	220	164	108	50	194
9	164	229	335	441	466	428	512	507	377	325	251	183	351
10	326	398	466	585	644	615	679	665	515	458	393	313	505
11	415	500	613	710	738	791	782	801	661	571	465	432	623
12	484	572	673	782	831	879	872	894	723	641	540	476	697
13	470	582	694	790	857	915	894	879	729	635	517	452	701
14	424	560	632	751	807	848	862	826	684	572	435	381	648
15	314	457	530	649	695	721	731	681	546	425	310	273	528
16	180	307	362	491	532	577	571	479	372	251	151	133	367
17	49	131	198	289	327	361	369	292	187	85	34	30	196
18	2	23	46	101	144	174	176	116	46	9	0	0	70
19	0	0	1	6	27	38	39	21	1	0	0	0	11
20	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0

In order to analyze the worst case scenario that can occur with PV power plants, the PV generation data of 24 hours are modified in order to create a 24 hour intermittent PV generation data. The modification is done simply by changing the PV generation values of odd hours to 5 MW which are within acceptable levels considering PV intermittency. Similar example of intermittent PV generation data for 24 hours can be found in [29] which belongs to the log of 3.6 kW inverter, saved in 05 December 2014.

Table 2.7 Monthly average generation values for 24 hours for the 50 MW PV power plant (MW).

H.	*JAN.*	*FEB.*	*MAR.*	*APR.*	*MAY.*	*JUN.*	*JUL.*	*AUG.*	*SEP.*	*OCT.*	*NOV.*	*DEC.*	*ANNUAL*
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	1	2	2	2	1	0	0	0	0	1
7	0	0	2	6	7	6	7	6	4	2	1	0	3
8	2	4	8	14	16	13	16	15	11	8	5	3	10
9	8	11	17	22	23	21	26	25	19	16	13	9	18
10	16	20	23	29	32	31	34	33	26	23	20	16	25
11	21	25	31	36	37	40	39	40	33	29	23	22	31
12	24	29	34	39	42	44	44	45	36	32	27	24	35
13	23	29	35	40	43	46	45	44	36	32	26	23	35
14	21	28	32	38	40	42	43	41	34	29	22	19	32
15	16	23	26	32	35	36	37	34	27	21	16	14	26
16	9	15	18	25	27	29	29	24	19	13	8	7	18
17	2	7	10	14	16	18	18	15	9	4	2	1	10
18	0	1	2	5	7	9	9	6	2	0	0	0	3
19	0	0	0	0	1	2	2	1	0	0	0	0	1
20	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0

The 24 hour intermittent PV generation values for the example 50 MW PV power plant are given in Table 2.8.

For the case studies, two daily PV generation data sets are required totally for representing most probable and possible worst cases of PV generation. These data sets are chosen as the 24 hours monthly average generation values of July for both cases.

Table 2.8 Monthly average intermittent generation values for 24 hours for the 50 MW PV power plant (MW).

H.	*JAN.*	*FEB.*	*MAR.*	*APR.*	*MAY.*	*JUN.*	*JUL.*	*AUG.*	*SEP.*	*OCT.*	*NOV.*	*DEC.*	*ANNUAL*
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	1	2	2	2	1	0	0	0	0	1
7	0	0	2	5	5	5	5	6	4	2	1	0	3
8	2	4	5	14	16	13	16	5	5	5	5	3	10
9	5	5	17	5	5	5	5	25	19	16	5	5	18
10	16	20	5	29	32	31	34	5	5	5	20	16	25
11	5	5	31	5	5	5	5	40	33	29	5	5	31
12	24	29	5	39	42	44	44	5	5	5	27	24	35
13	5	5	35	5	5	5	5	44	36	32	5	5	35
14	21	28	5	38	40	42	43	5	5	5	22	19	32
15	5	5	26	5	5	5	5	34	27	21	5	5	26
16	9	15	5	25	27	29	29	5	5	5	8	7	18
17	2	7	10	14	5	5	5	15	9	4	2	1	10
18	0	1	2	5	7	9	9	6	2	0	0	0	3
19	0	0	0	0	1	2	2	1	0	0	0	0	1
20	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0

CHAPTER 3

STANDARD AND MODIFIED SCUC ALGORITHMS CONSIDERING PV POWER PLANTS

3.1 The SCUC Algorithm

The SCUC algorithm is used by the system operators in day-ahead market. It solves the optimization problem having an objective function which is the sum of operational, no load, start up and shut down costs of generators. The algorithm finds the minimal cost which is the result of optimal schedule of generators that maintains the total demand and generation balance and required system reserves.

The SCUC algorithm utilizes information which are submitted by generator companies and system operators such as technical characteristics of generating units as well as system constraints (load – generation balance and network constraints) to derive a solution that ensures security of the system and maximizes social welfare; and it runs for 24 hours of next day. The algorithm matches the hourly demands and generations and allocates hourly required reserves while considering the constraints of generators and requirements of transmission system.

The SCUC algorithm is designed for conventional bulk generators, and therefore, the equations for constraints and generation characteristics are specific for thermal, nuclear or large hydropower generators [30]. However, the characteristics of PV power plants deviate from the conventional generators such as varying output levels with time, and intermittent nature and uncertain generation values. Therefore, in order to run the algorithm including PV power plants, some modifications on the constraints are required. In addition, in order to include the curtailment penalty price, additional modifications on the constraints and objective function are required.

In the following, the objective function and constraints of the SCUC algorithm are summarized first. The curtailment term in the scope of SCUC constraints is explained. The SCUC usage in day-ahead markets is summarized. Then the current studies and applications of SCUC including RES are given. The integration of PV power characteristics and curtailment penalty price into the standard algorithm is explained in separate sections. Finally, the complete SCUC problem including objective function and overview of constraints, and the new SCUC problem including modifications and additional constraints are given.

3.1.1 The Objective Function of the SCUC Algorithm: Cost Function

The cost function contains start up costs, shut down costs and piecewise operational costs, and no load costs of generators.

The no load cost stands for the cost that occurs when the unit is in the on state but not producing electricity. It generally occurs for the reserve requirements of transmission systems where the committed unit is made ready for reserve supply. In addition, a unit can be committed with zero generation because of its minimum down time constraint if shutting the committed generator down and providing energy from other generators causes more costs.

The operating costs of generators stand for the costs for generating electricity which can be in piecewise convex or non-convex curved form [30]. The piecewise characteristics of cost curves of generators are common since the generator companies submit the generation bids in discrete form by dividing the maximum capacity and the cost curve into segments. The convex and non-convex characteristics of the cost curves depend on the increment or decrement order of cost segments. If the costs between the segments are in increasing or decreasing order, then the cost curve of corresponding generator has convex characteristics. If the costs between the segments have more and less values without an order, then it has non-convex characteristics. In the SCUC algorithm, the convex and non-convex cost characteristics have different expressions as given in Appendix.

3.1.2 Start Up and Shut Down Cost Constraints of Generators

The start up cost is the cost that occurs when a unit is back on from the off state, and similarly the shut down cost is the cost that occurs when the unit is back off from the on state. With the start up and shut down cost constraints, the SCUC algorithm prevents unnecessary commitment of generators and change of operating status of generators.

3.1.3 Variable Start up Cost Constraints of Generators

Some generators cannot be online instantly while starting up, and the starting behavior depends on the time that they stay offline. In such situations, variable start up costs occur in the system that must be included in the SCUC algorithm. There are three types of variable start up behavior in common, namely, hot, warm and cold standing for quick, normal and late starts, respectively. The times of hot, warm and cold start of generators vary with the type and technical characteristics of generators. The detailed formulation of variable start up cost for unit i (the i_{th} generator) is given in Appendix.

3.1.4 Capacity Constraints of Generators

The capacity constraint is used for defining each unit's minimum and maximum generation limits in order to have a feasible scheduled value between these values for the corresponding unit.

3.1.5 Reserve Constraints of Generators

Recalling that in order to keep the balance of total electricity generation and demand, the SCUC or any UC algorithm tries to match the generation and the demand by using the estimated hourly demands and generation bids from companies. However, the estimated hourly demands may not give the exact demand values for the next 24 hours. Therefore, the system operator reserves some generation capacity as spare generation with determined amount depending on the system characteristics. There are two types of reserves, namely, spinning and operating reserves which are also known as hot and cold reserves, respectively.

The spinning reserve of a unit is the available generation amount that does not feed the grid. It is defined as the unloaded synchronized generation that can ramp up in ten minutes. This reserve is limited by the difference between the maximum capacity and current generation of the unit. It is also limited by the ten-minutes maximum sustained rate.

The operating reserve of a unit is also the unloaded generation amount that is either synchronized or unsynchronized and that can ramp up in ten minutes. When a unit is in the on state, its operating reserve is equal to the spinning reserve; and when it is in the off state, its operating reserve is equal to its quick start capability which is the generation amount that it can reach within ten minutes.

3.1.6 Ramping Constraints of Generators

The ramping up constraint is used for modeling the speed of generator for changing the current generation amount to a higher value, and similarly, the ramping down constraint is used for modeling the speed of generator for changing the current generation amount to a lower value.

3.1.7 Minimum Up and Down Time Constraints of Generators

The generators depending on the type and technology used may require some time before starting up or shutting down. This behavior is included in the SCUC algorithm with minimum up time and minimum down time terms.

The minimum up time means the time that a generator must stay online when it is in operation before shutting down, and the minimum down time means the time that a generator must stay offline before turning back on.

3.1.8 System Load Balance and Reserve Requirement Constraints

As the main requirement of the electricity grid, the generation and demand balance is formulated in the SCUC algorithm by matching the hourly generation and hourly demand.

The scheduled spinning (hot) reserve must be equal to or more than the spinning reserve requirement which will be assigned as spare hot generation and is paid when the corresponding generator uses its reserve to feed the grid.

The scheduled operating (cold) reserve must be equal to or more than the operating reserve requirement which will be assigned as spare cold generation and is paid when the corresponding generator uses its reserve to feed the grid.

3.1.9 Capacity Constraint of Transmission Lines

Recalling that the SCUC algorithm checks existence of overcurrent or congestion of transmission lines, it includes load flow analysis of transmission network. For the load flow analysis, a fast, accurate and reliable method is needed. Considering these requirements, the DC load flow is preferred to the AC load flow due to its simplicity, short time usage, and reliability [31].

In the DC load flow analysis:

- Line resistances (active power losses) are negligible (R << X),
- Voltage angle differences are assumed to be small (sin $(\theta) \sim \theta$ and cos $(\theta) \sim 1$),
- Bus voltage magnitudes are set to 1.0 per unit,
- Transformers' tap settings are ignored.

The DC load flow analysis consists of the voltage angle and the active power injection variables. The injected power is composed only of real part and mainly depends on the phase shifting of transformers, if there exists in the lines. The transmission capacity limitation for each line and the angles of phase shifting transformers are the variables that are included in the SCUC algorithm.

The SCUC algorithm does not include any formulation or equations for renewable energy sources. However, in new studies and publications stochastic SCUC algorithms including wind power are available. In this study, the characteristics and constraints of PV power plants as well as the curtailment penalty price are included in the SCUC algorithm.

3.2 Curtailment Occurrence in the Scope of SCUC Constraints

Recalling that the SCUC algorithm is an optimization problem which minimizes the total cost of electricity generation while satisfying a group of constraints, it minimizes any additional costs that can occur in the presence of PV power plants. This cost elimination can yield curtailment (limitation) of PV generation even there is potential for more generation. In this section, the reasons of PV curtailment are discussed.

The constraints of the SCUC algorithm are grouped under three subtitles as follows:

Cost constraints of generators:

- Start up and shut down costs,
- Operating (including no load) costs.

Technical constraints of generators:

- Minimum up and down times,
- Ramp up and down rates,
- Minimum generation amounts.

System constraints and requirements:

- Transmission line limitations,
- Reserve requirements.

As seen from the lists above, there are seven constraints which effect the utilization of available PV energy and cause curtailment. The main reason of curtailment is additional cost that occurs if utilization of PV energy requires more number of generators or more expensive generators to be committed. Possible situations of curtailment occurrence considering the listed seven constraints are given as follows:

a) Variations in PV generation can require more number of generators or more expensive generators to be committed compared with the case without PV generation because of the minimum up and down time constraints. This commitment can bring additional cost more than the decrement of total cost due to the free PV energy. As a result, since utilizing the PV energy brings extra cost, the SCUC algorithm prefers curtailing the PV energy.

b) The intermittent characteristics of PV energy require having fast responsive generators in the grid. Because of the ramp rate constraints of generators, more number of generators or more expensive generators can be required to be committed compared with the case without PV generation in order to compensate the fluctuations of PV generation. These commitments can bring additional cost. If this additional cost is higher than the decrement of the cost due to the PV energy, the SCUC algorithm curtails available PV energy.

c) Minimum generation constraints of generators can yield the curtailment of available PV energy since the minimum generation amount of conventional generators can be more than the demand.

d) The distances between greater loads and PV generators require having enough transmission line capacity to transmit the PV energy to loads. In some cases, PV generators and loads use most of the capacity of transmission lines. In these cases, generators which can use other available transmission lines to feed the loads can be required to be committed. This commitment may include more number of generators or more expensive generators compared with the case without PV generation.

e) Since PV generators have no reserve capability (some battery solutions are possible but only in small-scale applications such as prosumers in LV distribution), more number of generators or more expensive generators are to be committed to provide the reserve requirements.

By the listed five reasons of curtailment occurrence, it is clearly observed that because of the technical constraints of generators, and requirements and constraints of transmission system, the SCUC algorithm can commit more number of generators or more expensive generators compared with the case without PV energy which bring extra cost in terms of start up, shut down and operational costs in the presence of PV generation.

In order to avoid the curtailment which stands as an obstacle on increasing PV penetration level, there are six approaches available, four of which are technical and two of which are operational. The two technical approaches are obvious and consist of upgrading transmission lines and upgrading/replacing conventional generators with those having fast responsive characteristics. The third technical approach is optimization of phase shifters of transformers in order to reduce the curtailment by optimizing the power flow and minimizing the losses in transmission network [5]. The fourth technical approach is having storage systems for RES, especially for wind power, in order to store the curtailed energy and use it when needed [4].

The first operational approach of increasing PV penetration is revising the curtailment policies on the contract between PV energy company and system operator in order to give rights and incentives to PV energy company considering the curtailment [3]. The second operational approach is having an operational share between PV generators and conventional generators in order to reduce the curtailment and increase the PV penetration level [6].

As an overview, it can be said that the SCUC algorithm can curtail the available PV energy because of cost increment even it is technically feasible to increase the utilization of PV energy. As given in the lists above, the technical limitations on increasing PV penetration level are the transmission line capacities and slow responsive conventional generators; and since the SCUC algorithm starts curtailing the PV energy before reaching these limits, a method can be introduced in the SCUC algorithm for reducing the PV curtailment. This is the reason that yields the idea of adding curtailment penalty price to the SCUC algorithm and analyzing its effect on cost increment and curtailment reduction for different PV penetration levels.

3.3 Usage of the SCUC Algorithm Including RES in Day-Ahead Markets

There are three different ways for RES company to sell its energy which are namely feed-in tariff, bilateral agreement, and day-ahead market [32]. In the feed-in tariff case, commitment status of the RES does not depend on the feed-in tariff price since all available or committed RES energy (depends on the policy of system operator) is procured from the mutually agreed price between RES company and system operator. In the bilateral agreement case, a negotiable contract between the two market players is made on desired amount of power in which the terms of agreement is independent from ISO; but the agreed amount of power is verified by ISO considering the transmission capacity [30]. In the day-ahead market case, RES companies give generation bids ($/MWh) in the same way with conventional generators.

In practice, in day-ahead market, generators that have low operating cost (including RES) compared to other generators give the generation bid as zero in order to gain priority for the commitment in the corresponding hour. This is so, since the committed energy is paid at the Market Clearing Price (MCP) which is the highest offer of the committed generators in the corresponding hour. If there is curtailment of available RES energy and there is no incentive policy for RES, no payment is given for curtailed energy.

3.4 Current Studies and Applications of SCUC including RES

In this section, the literature review and the industrial practices of the SCUC algorithm considering RES are given. Recorded reasons, management and compensation of RES curtailments in electricity market of leading countries are provided.

Sudden unplanned and undesired variations occur at output power of RES because of its intermittent nature which means more sudden variations as the RES penetration level increases. This sudden change can be compensated to some level that depends on the conventional generators' minimum on and minimum off times, ramp up and ramp down rates which are called system flexibility provided that the transmission lines are not congested. If the sudden changes of the renewables cannot be compensated by the remaining system or the RES generation becomes high when the demand is low, then the curtailment occurs which is a limiting factor for RES penetration level.

Since the RES penetration level is desired to be increased, this limitation factor should be decreased, and consequently the RES curtailments have become a hot research topic. For instance in [4], a Compressed Air Energy Storage (CAES) is included with wind energy in the SCUC algorithm, and its effect on reducing wind curtailment is evaluated with the basic idea that the CAES stores wind energy when transmission congestion occurs and feeds the grid when the congestion is over. In [5], reducing wind curtailment with phase shifter optimization is evaluated. It proposes a relatively new SCUC algorithm that will minimize wind curtailment by optimizing the power flow in the transmission grid by the help of phase shifters. In [6], market mechanisms for RES in Germany, Spain and France are given and compared, and two new market mechanisms are proposed in order to decrease line congestion and consequently RES curtailments. For instance in Germany and France the RES can only connect to the grid with feed-in tariff option, but in Spain RES can also enter to day-ahead market with premium market price including minimum market price which is a privilege only for RES. While there is no financial compensation for curtailed energy in France, in Spain the compensation is available in real time operation with 15% of the market price, but for planned curtailment there is no financial compensation. In [32], economic valuation of wind curtailment rights is evaluated which examines the negotiations between RES companies and Independent System Operators (ISOs). Some revisions on contract between RES company and system operator are introduced for reducing the curtailment or compensating the revenue for curtailment. New market mechanisms are being developed for reducing the curtailment by giving priority to wind power [37].

Current studies about RES in day-ahead market includes mostly stochastic SCUC algorithms since they take into account the probability density function (PDF) of the RES and some load variations. For example in [7], the stochastic SCUC solution corresponding to selected wind and load scenarios is examined, and a new SCUC algorithm is proposed. In [8], another stochastic SCUC algorithm including both demand side and wind power PDFs is proposed. The proposed algorithm is tested on the IEEE Reliability Test System by adding three wind power plants on selected buses. For different wind power penetrations reaching up to 40% of total installed capacity, cost versus installed wind capacity and wind curtailment versus installed wind capacity are analyzed.

The SCUC algorithm in [8] includes penalty cost for carbon emissions which increases the cost if loads are fed from thermal generators when wind curtailment occurs. The average cost value of electricity ($/MWh) has global minimum points for different feed-in tariff prices of wind energy where the social welfare is maximized. The different minimal cost values are observed as the result of having same curtailed amount of wind energy for different feed-in tariff prices since the cost of wind energy is taken as zero in the SCUC algorithm and pricing of wind energy is made from the feed-in tariff price including curtailed energy.

As stated in Section 3.3, the SCUC is not only the area of research but also an industry practice in ISO managed day-ahead markets. For instance in [10], it is stated that Midwest ISO in the USA uses simultaneously co-optimized SCUC and SCED (Security Constrained Economic Dispatch) algorithms to clear and dispatch energy and operating reserves based on predefined constraints. Moreover, the company tries to improve the voltage profile by using the AC optimal power flow in the SCUC algorithm. In [11], the possible solutions of decreasing the required time for the solution of large-scale SCUC problems by Midwest ISO and ALSTOM Group are given. In [12], the usage and application of the SCUC in New York ISO (NYISO) area, and in [13] the customization and application of the SCUC algorithm by California ISO (CAISO) are given.

In [33], the reasons of wind and solar energy curtailments in the USA are provided and main reasons for the curtailments are given as inadequate transmission, line congestion and over generation on low demand period. The curtailment is stated as an increasing concern for wind and solar power plant owners. Existing method of compensation of curtailment is given which includes changing contract terms between wind energy companies and system operators. Methods to reduce the curtailment are suggested as introducing new market solutions to change the dispatch of generators based on RES, using curtailed energy as ancillary services, and better scheduling of generation and reserves. Expansion of transmission and upgrade of interconnections are suggested methods to reduce the curtailment as well.

The reasons of the curtailment of wind power at high penetration levels are given as start up times, minimum up and down times, and ramp rate limits of the conventional generators in [34]. In addition, another curtailment reason is stated as the generation limit set by system operators for the wind power plants considering the reserve requirements of transmission system and the intermittent characteristics of wind.

The reasons of wind and solar energy curtailment and how they are compensated in countries with high RES penetration level are given in [35]. Transmission congestion, minimum operating levels of conventional generators and voltage rises because of over generation in distribution side are stated as the main reasons for curtailment. Denmark is stated as a supporting country for increasing RES penetration by upgrading the interconnection of transmission lines and by enabling negative real price for electricity market which forces conventional generators to be fast responsive and being more capable for high RES penetrations. Negative real price occurs when a generator produces electricity although it is not committed and accept to pay for its produced electricity. This situation occurs when a generator company needs long time to start up or has more cost for starting up compared with the case that it pays for produced electricity. Since the generators prefers not to pay for its own electricity, this will force them to be fast responsive and to eliminate generations without being committed. In Ireland, a Secure Sustainable Electricity System Program (SSESP) is in progress which will manage the reserves and the ancillary services by optimizing the response characteristics of generators. Since the response characteristics will be used in optimal way, RES curtailments will be reduced. In Italy, as being one of the supporter country of high RES penetration level, significant amount of transmission capacity investments are made in order to reduce curtailment. In addition, investments in battery storage are made for increasing the flexibility of system, eliminating local congestion and reducing the need of spinning reserve.

In [36], examples of wind energy curtailment, amounts of curtailed wind energy in recent years, and compensation types of curtailment are provided for regions across the USA and some leading countries from EU. In some regions across the USA, the wind energy producers are paid by the system operators for the curtailed amount of wind energy if the contract between them includes compensation for the curtailment and the curtailed amount is beyond the predefined limit. In Germany, compensation for curtailment occurs only if the contract between RES company and system operator has a defined term for curtailment; and it is stated that 74 GWh of wind energy is curtailed between 2004 and 2006. In Ireland, wind generators are paid for the curtailed amount of energy from the Market Clearing Price (MCP) for corresponding hour instead of the fixed feed-in tariff or support price, and approximately 100 MWh of wind energy is curtailed in 2008. In Spain, in 2009, 54 GWh of wind energy was curtailed which was 0.15% of the total wind generation. In the first quarter of 2010, 1% of available wind generation is curtailed with a profit loss around 10 €M. In addition, the curtailments are expected to reach 6.8% of the total wind generation in future.

Considering the current studies and applications of SCUC including RES, by taking [8] as a main reference, in this thesis study, the effects of PV penetration level on the cost and the curtailment of available PV energy are analyzed. Compared to [8] not only the PV penetration level but also the number of connection buses are increased in a systematical way. Two different daily PV generation data are used consisting of most probable and possible worst PV generations. Curtailment penalty price is introduced as a penalty cost for curtailed PV energy, and its effect on cost increments and reduction of PV curtailments are evaluated for varying PV penetration levels for the two cases. The effect of curtailment penalty price on curtailment reduction and cost increment are evaluated for varying PV penetration levels for the two cases as well.

3.5 Integration of PV Generation into the SCUC Algorithm

In the SCUC algorithm there is no expression for RES. Therefore, the PV generation characteristics are to be integrated to the algorithm by adding one constraint and modifying two existing constraints. The integration consists of three steps.

Notations that are used in the three steps are given as follows:

NPV : Number of PV generators,

NH : Number of hours,

pv : Index for PV generators,

i : Index for conventional generators,

PPV_{pvt} : Output power of PV power plant pv_{th} at hour t,

NG : Number of conventional generators,

D_t : System load demand at hour t,

B' : Admittance matrix,

θ **:** Bus voltage angle vector,

B_{Δ} : Phase shifter incidence matrix,

Δ : Phase shifter angle vector,

PG : Generation vector,

PD : Demand vector,

PPV : PV generation vector.

First, the additional constraint (3.1) is used for defining the maximum and minimum amounts of PV generation for each time interval 't'.

$$PPV_{pvt}^{min} \leq PPV_{pvt} \leq PPV_{pvt}^{max}, \quad t \in \{1, \ldots, NH\}. \tag{3.1}$$

Second, the expression (3.2) is used for maintaining hourly balance of total generation and demand in the presence of PV generation. {Equation (3.2) replaces (A.17).}

$$\sum_i p_{it} + \sum_{pv} PPV_{pvt} = D_t, \quad pv \in \{1, \ldots, NPV\}, \quad i \in \{1, \ldots, NG\}. \tag{3.2}$$

Third, the expression (3.3) is used for the load flow analysis in the presence of PV generation in order to keep the transmission network within the capacities of lines. {Equation (3.3) replaces (A.20)}

$$B'\theta + B_{\Delta}\Delta = PG - PD + PPV. \tag{3.3}$$

3.6 Integration of PV Curtailment Penalty Price Constraint into the SCUC Algorithm

In the scope of SCUC optimization problem, it is seen that the algorithm tries to find the optimal schedule for generators with minimum total generation cost without violating any constraint.

The SCUC algorithm is modified by adding curtailment penalty price to minimize the curtailment and to maximize the RES penetration to the grid since the penalty price yields more cost while the curtailed amount of RES increases.

There are two expressions for integrating the PV curtailment penalty price into the algorithm. Notations that are used in the three steps are given as follows:

$PCurt_{pvt}$	: Curtailed power of PV power plant pv_{th} at hour t,
PPV_{pvt}	: Committed power for PV power plant pv_{th} at hour t,
PPV_{pvt}^{max}	: Maximum available output power of PV power plant pv_{th} at hour t,
CCurt	: Total cost of curtailment for 24 hours,
cpp	: Curtailment Penalty Price,
t	: Time index.

The expression (3.4) calculates the curtailed energy for PV power plant pv_{th} at hour t.

$$PCurt_{pvt} = PPV_{pvt}^{max} - PPV_{pvt}, \quad t \in \{0, \dots, NH\}. \tag{3.4}$$

The expression (3.5) calculates the total cost of curtailment for 24 hours.

$$CCurt = \sum_{pv}(PCurt_{pvt} \times cpp). \quad (3.5)$$

3.7 Summary of the Standard and the Modified SCUC Problems

The complete SCUC problem is summarized including the objective function and the constraints considered. The notations that are used in the objective function are given as follows:

c_{it} : Operational cost for unit i at hour t (including no load cost),
CSU_{it} : Total start up cost for unit i at hour t,
CSD_{it} : Total shut down cost for unit i at hour t.

The objective function is:

$$\sum_i c_{it} + \sum_i CSU_{it} + \sum_i CSD_{it}. \quad (3.6)$$

The list of constraints considered are given below:

- Operational costs of generators, {A.1a-A.2e}
- Variable start-up and shut-down costs of generators, {A.6-A.8h}
- Capacity limits of generators, {A.9}
- Operating and spinning reserve requirements of the network, {A.10-A.12}
- Ramp up and down constraints of generators, {A.13-A.14}
- Minimum up and down time constraints of generators, {A.15a-A.16d}
- Load balance and reserve requirements, {A.17-A.19}
- Transmission Line and DC Load Flow Constraints. {A.20-A.23}

The modified SCUC algorithm differs in objective function since it includes the curtailment penalty price and given as follows:

$$\sum_i c_{it} + \sum_i CSU_{it} + \sum_i CSD_{it} + \sum_{pv}(PCurt_{pvt} \times cpp). \qquad (3.7)$$

with additional four new constraints:

- Hourly generation constraints of PV generation, {3.1}
- Modified balance constraint of generation and demand with PV, {3.2}
- Modified transmission line and DC load flow constraints with PV, {3.3}
- Curtailment Penalty Price (CPP) constraint. {3.4}

CHAPTER 4

CASE STUDIES

In this thesis study, the IEEE 118 Bus Test System is used in order to test the standard and modified SCUC algorithms.

4.1 The IEEE 118 Bus Test System

The IEEE 118 Bus Test System, which has 54 generators, 186 branches and 91 load sides, is used as a test system [30], [38]. The total installed capacity of this system is 9.9 GW, and the total daily energy consumption is 95,792 MWh. The single line diagram of the system is given in Figure 4.1 [38].

The SCUC algorithm requires constraints and technical characteristics of the generators, the transmission system as well as the 24 hour load data, and the generation offers. The required data are available within the IEEE 118 Bus Test System such as the annual or monthly average load data for 24 hours and generation offers, except the hourly generation amounts of PV power plants. That is why the daily PV generation data is created as described in Section 2.4.

4.2 Case Studies

There are three simulation scenarios which are based on daily SCUC analysis.

Scenario A (Base Case): Daily SCUC analysis with conventional generators. PV power plants are not connected.

Scenario B (Sc. B): Daily SCUC analysis in the presence of PV power plants.

Scenario C (Sc. C): Daily SCUC analysis in the presence of PV power plants and curtailment penalty price (CPP).

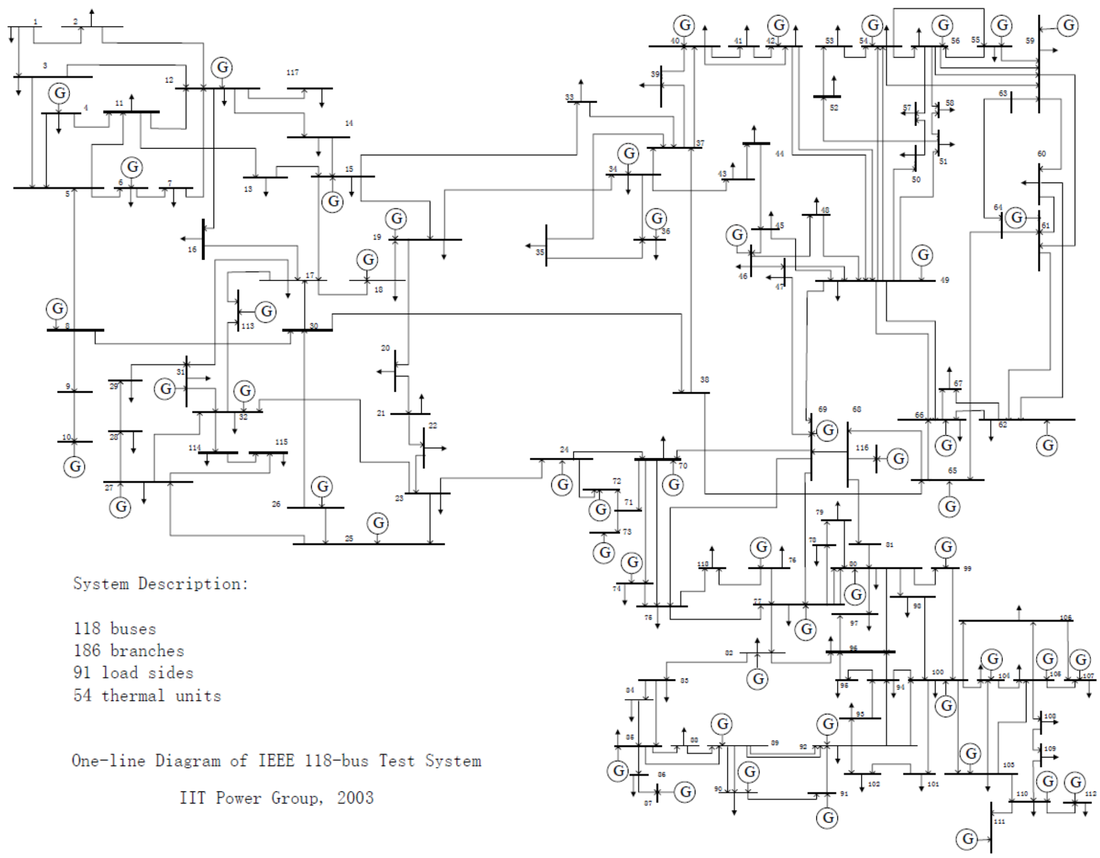

Figure 4.1 Single line diagram of the IEEE 118 Bus Test System.

Both scenarios B and C are run under two cases:

Case 1: General (most probable) 24 hours PV generation values are used.

Case 2: Modified (possible worst case) 24 hours PV generation values are used which bring sudden changes in generated power.

In Case 1, the daily PV generation data for 24 hours is given to the SCUC algorithm without considering intermittency. The average values are used from Table 2.7. In Case 2, the intermittency is considered and the PV generation data for 24 hours is given with high differences between hours. The data in Table 2.8 is used. The data on Tables 2.7 and 2.8 are created for 50 MW PV capacity; for other PV capacities linear scaling is used.

The difference between Scenarios B and C is the curtailment penalty price existence in the SCUC algorithm. In Scenario B, the objective function of SCUC algorithm is the same with the standard SCUC algorithm but the constraints are the modified ones that are adjusted for varying PV characteristics. In Scenario C, the objective function includes the expression (3.5) and the additional constraints (3.1 – 3.4) for curtailment penalty price.

In Scenarios B and C, the price of PV energy ($/MWh) is adjusted as the cheapest generation compared to other conventional generator prices in order to give the first priority to PV generators. In addition, in Scenario C, the CPP is set to the most expensive generation offer of generators. That is, the PV energy company will be paid on the basis of most expensive price for the amount of curtailed energy.

Scenarios B and C under the two cases are run for 24 different PV generation capacities starting from 50 MW up to 750 MW, and also for 800 MW (for one PV power plant), in four different tests that differ by the number of PV power plants and the number of connection buses in the test system.

In order to observe the effect of CPP value on the reduction of curtailed PV energy and the increment on total cost, three additional tests are conducted that differ in the value of CPP.

The conducted seven tests and their scopes are summarized in Table 4.1.

Table 4.1 Scopes of the conducted tests.

Test No.	Included Analyses	No. of PV Power Plants	Connection Buses of PV Power Plants	Capacity of each PV Power Plant	No. of Different PV Capacities	CPP Value ($/MWh) in Sc. C	Total No. of Analyses
1	(Base Case) + (Case 1 - Sc. B and C) + (Case 2 - Sc. B and C)	3	14, 54, 95	50+50k (k=0,..,5), 325+25k (k=0,..,17)	24	80	97
2	(Case 1 - Sc. B and C) + (Case 2 - Sc. B and C)	3	15, 54, 96	50+50k (k=0,..,5), 325+25k (k=0,..,17)	24	80	96
3	(Case 1 - Sc. B and C) + (Case 2 - Sc. B and C)	5	5, 15, 23, 49, 85	50+50k (k=0,..,7), 425+25k (k=0,..,15)	24	80	96
4	(Case 1 - Sc. B and C) + (Case 2 - Sc. B and C)	8	5, 15, 23, 49, 59, 77, 85, 92	50+50k (k=0,..,7), 425+25k (k=0,..,15)	24	80	96
5	(Case 1 - Sc. C) + (Case 2 - Sc. C)	8	5, 15, 23, 49, 59, 77, 85, 92	50+50k (k=0,..,7), 425+25k (k=0,..,15)	24	40	48
6	(Case 1 - Sc. C) + (Case 2 - Sc. C)	8	5, 15, 23, 49, 59, 77, 85, 92	50+50k (k=0,..,7), 425+25k (k=0,..,15)	24	160	48
7	(Case 1 - Sc. C) + (Case 2 - Sc. C)	8	5, 15, 23, 49, 59, 77, 85, 92	50+50k (k=0,..,7), 425+25k (k=0,..,15)	24	320	48

Table 4.1 highlights the structure of performed tests. For Test 1, the SCUC algorithm runs for two cases each of which contains Scenarios B and C. Totally, four different analyses are run on the test system with three PV power plants each of which has 50 MW capacity at the beginning and connected to buses number 14, 54 and 95. The four different analyses with three PV power plants are run for 24 different PV capacities which make 4*24=96 analyses, and also considering the base case (without PV), there are 97 SCUC analyses. The total number of analyses for other tests are determined similarly.

Consequently, the standard and modified SCUC algorithms are run on the test system for 529 different analyses totally including seven tests each of which has two scenarios under two cases and 24 different PV capacity combinations. The results of these tests are compared from the following nine perspectives:

1. The effect of PV penetration level on total electricity generation cost (all tests, cases and scenarios),
2. The effect of PV penetration level on PV curtailment (all tests, cases and scenarios),
3. The PV capacity which yields minimum total electricity generation cost (all tests, cases and scenarios),
4. The maximum PV capacity with zero curtailment (all tests, cases and scenarios),
5. The effect of CPP on total generation cost and PV curtailment for different PV penetration levels (all tests, cases and scenarios),
6. The effect of intermittency on total generation cost and amount of PV curtailment for different PV penetration levels (all tests, cases and scenarios),
7. The relation between additional cost because of CPP and reduction amount of PV curtailment for different PV penetration levels (all tests, cases and scenarios),
8. The effect of dispersing PV capacity on reduction of PV curtailment and the effectiveness of CPP (Tests 2 to 4, all cases and scenarios),
9. The effect of CPP value on PV curtailment for different PV penetration levels (Tests 4 to 7, all cases and scenarios).

4.3 Software Environment

The 24 hour PV generation values are created by using System Advisor Model (SAM) software which is developed by National Renewable Energy Laboratory (NREL) in the USA. The data for the IEEE 118 Bus Test System is taken from [38] and used in the test cases. The SCUC algorithms run for 529 cases containing all necessary variables, constants, indices, constraints and limitations of generators, transmission system and PV generators using MATLAB (r2013b) software.

The SCUC algorithms are converted to CPLEX compatible problem file format (.lp) in MATLAB and the '.lp' files for the corresponding 529 cases which include nearly 71,000 constraints (per one analysis) are created. Then these '.lp' files are given as input for IBM CPLEX (v12.6) optimization software, and the optimal generator schedules with the total minimum electricity generation costs are found in 36 hours with a desktop PC having Intel i5 Quad–Core processor running at 3.3 GHz and 8 GB of DDR3 Ram. After the solution is obtained, the output solution file of each analysis from IBM CPLEX software (.sol file) is read in MATLAB for analyzing and printing the results. In addition, for creating the tables that give the ratios between additional costs by penalty price and reduction amounts of PV curtailment for increasing PV penetration levels, MS Excel is used with the read values from '.sol' file by MATLAB.

4.4 Tests

The seven tests are grouped under two subtitles depending on their scope. The first group consists of Tests 1, 2, 3 and 4 which have different PV penetration levels with non-decreasing number of connection buses to the test system. The second group consists of Tests 4, 5, 6 and 7 in which all the conducted tests have the same configuration with Test 4 but have different CPP.

In this section some abbreviations are used for reducing the complexity of the text which are listed as follows:

Scenario B - Case 1: B1, Scenario B - Case 2: B2,
Scenario C - Case 1: C1, Scenario C - Case 2: C2.

Test results are given in tabular form. Some terms which are used in the tables are defined below:

Total Curtailed PV (MWh): Amount of daily total curtailed PV energy.

Percentage of Reduction in PV Curtailment (Sc. C): The percentage of reduction in PV curtailment when CPP is added to the SCUC algorithm in Scenario C. The percentage is obtained by dividing the difference between the curtailed energies of Scenarios B and C to the curtailed energy in Scenario B.

Percentage of Reduction in PV Curtailment (T5, T6, T7): The percentage of reduction in PV curtailment when curtailment penalty price is changed to 40, 160 and 320 $/MWh from 80 $/MWh. The percentage is obtained by dividing the differences between the curtailed energies in Test 4 - Scenario B and Tests 5, 6 and 7 - Scenario C to the curtailed energy in Test 4 - Scenario B.

Percentage of Cost Increment (Sc. C): The percentage of additional cost caused by CPP in Scenario C. The percentage is obtained by dividing the difference between the costs for Scenarios C and B to the cost for Scenario B.

Percentage of Cost Increment (T5, T6, T7): The percentage of additional cost caused by curtailment penalty price in Tests 5, 6 and 7 - Scenario C. The percentage is obtained by dividing the differences between the costs for Tests 5, 6 and 7 - Scenario C and Test 4 - Scenario B to the cost for Test 4 - Scenario B.

4.4.1 Group 1

4.4.1.1 Test 1: Three PV Power Plants

There are three PV generators connected to buses number 14, 54, and 95, which are the selected buses in [7] for wind power generation with capacities providing up to 21.7% of the total daily energy demand of the IEEE 118 Bus Test System.

In order to observe the penetration level effect of PV, the total capacity of three PV generators is varied from 150 MW to 2,250 MW with an increment amount of 150 MW until 900 MW capacity, and from 975 MW to 2,250 MW with an increment amount of 75 MW. The ratio of 2,250 MW maximum PV capacity to the total installed capacity is 18.4%. The ratio of 11,205 MWh total maximum daily PV energy to the daily energy consumption is 11.7% if there is no curtailment.

In Test 1, 97 daily SCUC analyses which consist of four different analyses for 24 different PV capacities and a base case are conducted. The results are given in Tables 4.1 and 4.2 for Case 1 and Case 2, respectively.

The curtailment penalty price reduces the daily total curtailed energy in Scenario C for each PV capacity. The amount of reduction decreases as the total PV capacity increases which is the result of reaching the technical limitations of available generators and transmission lines.

The total curtailed energies in C2 are less than the curtailed energies in C1 which is the result of having less PV generation in Case 2. The cost increments are also less in Case 2.

There are cases where the curtailed energy may yield economically unfeasible situation. For example, for 1,800 MW PV capacity there is 1,593 MWh curtailed energy in B1 which is close to the maximum hourly generation of all three PVs. In C1, the curtailed energy is reduced to 1,322 MWh by CPP. With the curtailment penalty price, the minimal cost occurs at 1,275 MW and 1,200 MW in C1 and C2, respectively.

The maximum PV capacities with zero curtailment are observed as 1,050 MW for B1 and B2 as seen in Tables 4.2 and 4.3, and these capacities are increased to 1,125 MW in C1 and C2.

Table 4.2 The effects of curtailment penalty price on curtailed energies and total costs in Test 1 - Case 1.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
150	0	0	-	1,608,676	1,608,648	0.00
300	0	0	-	1,591,527	1,591,550	0.00
450	0	0	-	1,574,769	1,574,679	0.00
600	0	0	-	1,558,258	1,558,213	0.00
750	0	0	-	1,541,926	1,541,923	0.00
900	0	0	-	1,526,061	1,526,009	0.00
975	0	0	-	1,518,281	1,518,307	0.00
1050	0	0	-	1,510,700	1,510,779	0.00
1125	24	0	100.00	1,503,821	1,504,597	0.05
1200	89	17	80.90	1,497,432	1,502,081	0.31
1275	175	71	59.43	1,491,482	1,501,390	0.66
1350	278	161	42.09	1,485,823	1,503,630	1.20
1425	464	298	35.78	1,481,194	1,511,635	2.06
1500	650	455	30.00	1,476,733	1,521,742	3.05
1575	851	656	22.91	1,472,541	1,533,718	4.15
1650	1080	870	19.44	1,468,794	1,546,875	5.32
1725	1314	1096	16.59	1,465,146	1,561,374	6.57
1800	1593	1322	17.01	1,462,004	1,577,514	7.90
1875	1917	1574	17.89	1,459,242	1,596,738	9.42
1950	2212	1861	15.87	1,456,457	1,619,179	11.17
2025	2534	2195	13.38	1,453,756	1,643,059	13.02
2100	2897	2549	12.01	1,451,445	1,668,623	14.96
2175	3284	2903	11.60	1,449,425	1,696,406	17.04
2250	3671	3275	10.79	1,447,500	1,723,633	19.08

4.4.1.2 Test 2: Three PV Power Plants with Different Bus Connections

It is observed from the results of Test 1 that the CPP did not yield dramatic curtailment reductions. By inspecting the reason for such high amounts of curtailments, it is noticed that the PV generation may have been curtailed at the connection buses since the buses of three PV Power plants are selected the same as in [7]. The PV capacity is needed to be more than the wind power even for the less energy ratio 11.7% since the PV energy is not available for 24 hours. The connection buses in Test 1 which are 15, 54 and 95 are examined and it is observed that the transmission lines connected to these buses have 1,200, 1,050 and 350 MW total capacities, respectively. Since the maximum PV capacity for one PV power plant is 750 MW in Test 1, in Test 2 the connection bus 95 is changed to bus 96 for which the connected transmission lines have 875 MW total capacity.

In Test 2, 96 daily SCUC analyses which consist of 4 different analyses for 24 different PV capacities are conducted. Results are given in Tables 4.4 and 4.5 for Case 1 and Case 2, respectively.

Table 4.3 The effects of curtailment penalty price on curtailed energies and total costs in Test 1 - Case 2.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
150	0	0	-	1,615,964	1,615,978	0.00
300	0	0	-	1,605,992	1,605,962	0.00
450	0	0	-	1,596,196	1,596,258	0.00
600	0	0	-	1,586,607	1,586,641	0.00
750	0	0	-	1,577,204	1,577,187	0.00
900	0	0	-	1,568,488	1,568,522	0.00
975	0	0	-	1,564,361	1,564,387	0.00
1050	0	0	-	1,560,492	1,560,476	0.00
1125	16	0	100.00	1,556,803	1,557,193	0.03
1200	59	26	55.93	1,553,404	1,556,657	0.21
1275	112	70	37.50	1,550,023	1,556,881	0.44
1350	175	113	35.43	1,546,832	1,557,213	0.67
1425	280	195	30.36	1,543,993	1,561,519	1.14
1500	390	293	24.87	1,541,327	1,566,928	1.66
1575	501	398	20.56	1,538,736	1,572,892	2.22
1650	652	506	22.39	1,536,435	1,579,117	2.78
1725	803	608	24.28	1,534,301	1,586,130	3.38
1800	958	727	24.11	1,532,278	1,594,986	4.09
1875	1136	862	24.12	1,530,253	1,604,738	4.87
1950	1316	1028	21.88	1,528,214	1,616,544	5.78
2025	1491	1218	18.31	1,526,190	1,628,703	6.72
2100	1680	1390	17.26	1,524,226	1,641,040	7.66
2175	1896	1582	16.56	1,522,438	1,654,594	8.68
2250	2103	1775	15.60	1,520,636	1,668,278	9.71

The curtailment reductions are more compared with Test 1 – Case 1 in Table 4.2 since the location of the buses for PV generators are selected considering the capacity of transmission lines and the closeness to loads in order to minimize the limitations of transmission system. In addition, the cost increments are less compared with Table 4.2 since the curtailed energies are greatly reduced.

In B1, the maximum PV capacity with zero curtailment is observed as 1,425 MW, and by CPP in C1 this capacity is increased to 1,800 MW with 0.02% increase on total cost.

The maximum reduction in curtailed energy is 208 MWh for 2,250 MW PV capacity with 2.17%. cost increment.

Table 4.4 The effects of curtailment penalty price on curtailed energies and total costs in Test 2 - Case 1.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
150	0	0	-	1,608,521	1,608,484	0.00
300	0	0	-	1,591,228	1,591,278	0.00
450	0	0	-	1,574,475	1,574,479	0.00
600	0	0	-	1,557,912	1,557,950	0.00
750	0	0	-	1,541,641	1,541,684	0.00
900	0	0	-	1,525,811	1,525,784	0.00
975	0	0	-	1,518,006	1,518,006	0.00
1050	0	0	-	1,510,470	1,510,419	0.00
1125	0	0	-	1,502,995	1,503,016	0.00
1200	0	0	-	1,495,718	1,495,646	0.00
1275	0	0	-	1,488,537	1,488,545	0.00
1350	0	0	-	1,481,484	1,481,444	0.00
1425	0	0	-	1,474,470	1,474,456	0.00
1500	3	0	100.00	1,467,607	1,467,604	0.00
1575	13	0	100.00	1,460,894	1,460,928	0.00
1650	18	0	100.00	1,454,211	1,454,247	0.00
1725	25	0	100.00	1,447,601	1,447,706	0.00
1800	52	0	100.00	1,441,271	1,441,629	0.02
1875	124	9	92.74	1,435,172	1,436,870	0.12
1950	153	31	79.74	1,429,043	1,434,367	0.37
2025	209	97	53.59	1,423,006	1,433,513	0.74
2100	314	171	45.54	1,417,332	1,433,819	1.16
2175	420	255	39.29	1,411,791	1,435,624	1.69
2250	549	341	37.89	1,406,405	1,436,881	2.17

The curtailment reductions are more in Case 2 compared with Case 1, and the cost increments are less. Therefore, it can be said that the CPP effect on curtailment reduction is more when the PV generation has intermittent characteristics.

The maximum PV capacity with zero curtailment in B2 is 1,200 MW, and this capacity is increased to 1,800 MW by the help of CPP in C2 with 0.23% cost increment.

The maximum reduction in curtailed energy is 401 MWh for 2,250 MW PV capacity with 2.01% cost increment.

Table 4.5 The effects of curtailment penalty price on curtailed energies and total costs in Test 2 - Case 2.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
150	0	0	-	1,615,935	1,615,994	0.00
300	0	0	-	1,605,944	1,605,945	0.00
450	0	0	-	1,596,128	1,596,127	0.00
600	0	0	-	1,586,530	1,586,533	0.00
750	0	0	-	1,577,078	1,577,049	0.00
900	0	0	-	1,568,129	1,568,084	0.00
975	0	0	-	1,563,900	1,563,832	0.00
1050	0	0	-	1,559,680	1,559,664	0.00
1125	0	0	-	1,555,595	1,555,616	0.00
1200	0	0	-	1,551,599	1,551,559	0.00
1275	1	0	100.00	1,547,707	1,547,681	0.00
1350	28	0	100.00	1,543,853	1,543,799	0.00
1425	36	0	100.00	1,540,063	1,540,056	0.00
1500	65	0	100.00	1,536,360	1,536,460	0.00
1575	106	0	100.00	1,532,789	1,533,107	0.02
1650	155	0	100.00	1,529,300	1,530,202	0.06
1725	229	10	95.63	1,525,944	1,527,886	0.13
1800	316	0	100.00	1,522,642	1,526,193	0.23
1875	380	15	96.05	1,519,298	1,526,364	0.47
1950	437	73	83.30	1,516,100	1,527,660	0.76
2025	479	121	74.74	1,512,934	1,529,022	1.06
2100	526	172	67.30	1,509,904	1,530,590	1.37
2175	579	218	62.35	1,507,079	1,532,464	1.68
2250	670	269	59.85	1,504,445	1,534,702	2.01

By comparing the maximum PV capacities with zero curtailment for B1, B2, C1 and C2 in Test 2 with the capacities in Test 1 which are 1,050 MW in B1 and B2, and 1,125 MW in C1 and C2, it is observed that the maximum PV capacities with zero curtailment are greatly increased.

The curtailment penalty price not only decreases the curtailed PV energy but also keeps it zero until 1,800 MW for both cases as seen in Tables 4.4 and 4.5. Although the curtailment penalty price increases the cost when curtailment occurs, considering the reduction in curtailed amount of PV energy the cost increment may be acceptable.

In Case 2, since the effect of intermittency increases with higher capacities of PV power plants and requires more compensation compared with Case 1, more curtailments of PV energy are observed for the same PV penetration levels.

4.4.1.3 Test 3: Five PV Power Plants

In this test, the number of PV generators is increased to five and connection buses (5, 15, 23, 49, and 85) are selected considering the transmission capacity and closeness to the load buses. The PV capacity is varied from 250 MW to 2,000 MW with increment amount of 250 MW, and 2,125 MW to 4,000 MW with increment amount of 125 MW for each PV generator. This configuration yields 28.6% maximum installed capacity ratio and 20.8% maximum daily energy ratio provided that there is no curtailment. With this test, for the same PV capacity amounts with Test 2, the effect of allocating PV generation to higher number of buses on generation costs and PV curtailments are examined.

In Test 3, 96 daily SCUC analyses are conducted as in Test 2. The results are given in Tables 4.6 and 4.7 for Case 1 and Case 2, respectively.

As the dispersion of PV generation is increased by having more number of PV power plants, the total PV capacity with zero curtailment is increased to 2,000 MW in B1 and 2,625 MW in C1 with 0.54% cost increment. It is also observed that the curtailment reductions for the PV penetration levels more than 3,250 MW are significantly low and the corresponding costs increase with higher rate compared with costs increments of less PV penetration levels. This is so, because the limitations of transmission lines and/or generators are reached.

Table 4.6 The effects of curtailment penalty price on curtailed energies and total costs in Test 3 - Case 1.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
250	0	0	-	1,596,866	1,596,879	0.00
500	0	0	-	1,568,905	1,568,890	0.00
750	0	0	-	1,541,655	1,541,696	0.00
1000	0	0	-	1,515,150	1,515,157	0.00
1250	0	0	-	1,489,568	1,489,546	0.00
1500	0	0	-	1,464,965	1,464,974	0.00
1750	0	0	-	1,441,247	1,441,244	0.00
2000	0	0	-	1,418,819	1,418,830	0.00
2125	26	0	100.00	1,408,279	1,408,336	0.00
2250	80	0	100.00	1,397,966	1,399,250	0.09
2375	79	0	100.00	1,388,242	1,390,382	0.15
2500	196	0	100.00	1,378,819	1,384,729	0.43
2625	354	0	100.00	1,370,054	1,377,496	0.54
2750	474	108	77.22	1,361,782	1,376,027	1.05
2875	604	258	57.28	1,353,831	1,378,528	1.82
3000	728	442	39.29	1,346,109	1,384,441	2.85
3125	978	628	35.79	1,338,576	1,390,464	3.88
3250	1290	831	35.58	1,331,685	1,399,391	5.08
3375	1190	1096	7.90	1,324,775	1,415,363	6.84
3500	1527	1404	8.06	1,317,931	1,433,287	8.75
3625	1885	1738	7.80	1,311,555	1,453,101	10.79
3750	2259	2093	7.35	1,305,748	1,477,229	13.13
3875	2653	2515	5.20	1,299,996	1,503,764	15.67
4000	3110	2917	6.21	1,294,802	1,530,951	18.24

The curtailed energies are significantly reduced with very small cost increments such as elimination of 354 MWh curtailed energy by 0.54% cost increment for 2,625 MW

PV capacity. The maximum reduction in curtailed energy, 459 MWh, is achieved for 3,250 MW PV capacity with 5.08% cost increment.

In Case 2, the curtailment reductions increase compared with Case 1 since the CPP is more effective when the PV generation is intermittent. In comparison with Table 4.5, it is observed that the total curtailed energies for the same PV capacities are lower. This is the result of having more number of PV power plants which enable more transmission lines to be utilized.

Table 4.7 The effects of curtailment penalty price on curtailed energies and total costs in Test 3 - Case 2.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
250	0	0	-	1,609,243	1,609,267	0.00
500	0	0	-	1,592,973	1,592,940	0.00
750	0	0	-	1,576,997	1,577,011	0.00
1000	0	0	-	1,562,056	1,562,025	0.00
1250	0	0	-	1,547,750	1,547,720	0.00
1500	0	0	-	1,534,261	1,534,261	0.00
1750	123	0	100.00	1,522,638	1,523,086	0.03
2000	372	1	99.73	1,512,259	1,516,477	0.28
2125	512	19	96.29	1,507,460	1,516,326	0.59
2250	667	78	88.31	1,502,951	1,518,358	1.03
2375	866	141	83.72	1,498,681	1,521,713	1.54
2500	1070	257	75.98	1,494,698	1,528,726	2.28
2625	1302	381	70.74	1,490,815	1,537,007	3.10
2750	1538	542	64.76	1,487,023	1,546,835	4.02
2875	1813	704	61.17	1,483,223	1,557,240	4.99
3000	2022	868	57.07	1,479,539	1,568,078	5.98
3125	2264	1029	54.55	1,476,102	1,579,894	7.03
3250	2578	1221	52.64	1,472,674	1,593,989	8.24
3375	2869	1458	49.18	1,469,454	1,610,260	9.58
3500	3155	1704	45.99	1,466,147	1,626,985	10.97
3625	3441	1955	43.19	1,463,098	1,643,958	12.36
3750	3741	2192	41.41	1,459,978	1,661,338	13.79
3875	4058	2470	39.13	1,456,918	1,680,544	15.35
4000	4294	2740	36.19	1,453,899	1,700,962	16.99

The curtailed energies are significantly reduced with small cost increments such as elimination of 813 MWh curtailed energy by 2.28% cost increment for 2,500 MW PV capacity in Case 2. The maximum reduction in curtailed energy, 1,588 MWh, is achieved for 3,875 MW PV capacity with 15.35% cost increment.

4.4.1.4 Test 4: Eight PV Power Plants

In this test, the number of PV generators is increased to eight and connection buses (5, 15, 23, 49, 59, 77, 85, and 92) are also selected considering the transmission capacity and closeness to the load buses. The PV capacity is varied from 400 MW to 3,200 MW with increment amount of 400MW, and 3,400 MW to 6,400 MW with increment amount of 200 MW for each PV generator. This configuration yields 39.1% maximum installed capacity ratio and 33.2% maximum daily energy ratio if there is no curtailment. With this test, for the same PV capacity amounts with Tests 2 and 3, the effects of allocation of PV generation to more number of buses on generation costs and PV curtailments are examined.

In Test 4, 96 daily SCUC analyses are conducted as well and the results are given in Tables 4.8 and 4.9 for Case 1 and Case 2, respectively.

In Case 1, the percentages of curtailment reduction decrease dramatically for PV penetration levels more than 4,400 MW. This shows that the limitations of transmission system and/or generators are reached. By comparing Tables 4.8 and 4.6, it is observed that the curtailed amounts for the same or almost the same PV capacities are less in Table 4.8 which is the result of having the same PV capacity from more number of PV power plants.

In B1, the maximum PV capacity with zero curtailment is observed as 3,200 MW, and this capacity increase to 3,600 MW in C1 with 0.09% cost increment.

The maximum reduction in curtailed energy, 678 MWh, is achieved for 4,400 MW PV capacity with 2.77% cost increment.

Table 4.8 The effects of curtailment penalty price on curtailed energies and total costs in Test 4 - Case 1.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
400	0	0	-	1,580,043	1,580,021	0.00
800	0	0	-	1,536,365	1,536,311	0.00
1200	0	0	-	1,494,614	1,494,548	0.00
1600	0	0	-	1,455,221	1,455,191	0.00
2000	0	0	-	1,417,161	1,417,162	0.00
2400	0	0	-	1,380,722	1,380,719	0.00
2800	0	0	-	1,346,398	1,346,422	0.00
3200	0	0	-	1,314,302	1,314,285	0.00
3400	45	0	100.00	1,299,248	1,299,207	0.00
3600	111	0	100.00	1,284,798	1,285,898	0.09
3800	144	6	95.83	1,271,129	1,275,605	0.35
4000	357	9	97.48	1,258,270	1,266,270	0.64
4200	641	103	83.93	1,246,651	1,263,578	1.36
4400	1012	334	67.00	1,235,648	1,269,887	2.77
4600	1075	678	36.93	1,224,831	1,282,584	4.72
4800	1491	947	36.49	1,214,709	1,300,178	7.04
5000	1946	1394	28.37	1,205,311	1,321,061	9.60
5200	2352	1888	19.73	1,196,224	1,350,417	12.89
5400	2980	2432	18.39	1,187,867	1,386,622	16.73
5600	3433	3074	10.46	1,179,756	1,428,793	21.11
5800	4100	3780	7.80	1,172,356	1,477,843	26.06
6000	4858	4511	7.14	1,165,374	1,529,768	31.27
6200	5602	5267	5.98	1,158,652	1,582,978	36.62
6400	6161	6023	2.24	1,152,267	1,636,606	42.03

In B2, the curtailment starts at 2,000 MW which is less than B1 and there is no 100% curtailment reduction percentage in C2. This much of curtailment is the result of intermittency since the intermittent characteristics of PV generation requires fast responsive generators for compensation and yield more curtailment.

In Table 4.8, for 4,000 MW PV capacity there is almost no curtailment in C1, but for the same capacity in C2, even with the curtailment penalty price, the curtailed energy is 2,121 MWh as seen in Table 4.9 which may lead an economically unfeasible situation.

Table 4.9 The effects of curtailment penalty price on curtailed energies and total costs in Test 4 - Case 2.

Tot. PV Cap. (MW)	*Tot. Curt. (Sc. B) (MWh)*	*Tot. Curt. (Sc. C) (MWh)*	*Curt. Reduction (%)*	*Tot. Cost (Sc. B) ($)*	*Tot. Cost (Sc. C) ($)*	*Cost Increment (%)*
400	0	0	-	1,599,390	1,599,418	0.00
800	0	0	-	1,573,990	1,573,997	0.00
1200	0	0	-	1,550,532	1,550,517	0.00
1600	0	0	-	1,528,821	1,528,792	0.00
2000	158	1	99.37	1,510,513	1,511,922	0.09
2400	788	109	86.17	1,496,219	1,515,095	1.26
2800	1385	413	70.18	1,482,554	1,531,703	3.32
3200	2102	776	63.08	1,470,996	1,562,211	6.20
3400	2557	1083	57.65	1,465,520	1,584,443	8.11
3600	3022	1417	53.11	1,460,029	1,607,743	10.12
3800	3390	1781	47.46	1,454,751	1,631,749	12.17
4000	3834	2121	44.68	1,449,558	1,657,860	14.37
4200	4257	2563	39.79	1,444,559	1,686,554	16.75
4400	4679	2985	36.20	1,439,695	1,716,340	19.22
4600	5092	3413	32.97	1,435,119	1,746,378	21.69
4800	5532	3845	30.50	1,430,772	1,776,726	24.18
5000	5954	4293	27.90	1,426,722	1,807,195	26.67
5200	6480	4715	27.24	1,422,983	1,838,692	29.21
5400	7069	5186	26.64	1,419,350	1,871,584	31.86
5600	7628	5638	26.09	1,415,820	1,905,992	34.62
5800	8146	6085	25.30	1,412,241	1,941,854	37.50
6000	8761	6631	24.31	1,408,740	1,980,177	40.56
6200	9351	7165	23.38	1,405,250	2,020,523	43.78
6400	9872	7712	21.88	1,401,867	2,061,550	47.06

In Case 2, the curtailed energies are significantly reduced with low cost increments such as elimination of 1,326 MWh curtailed energy by 6.20% cost increment for 3,200 MW PV capacity.

The maximum reduction in curtailed energy, 2,186 MWh, is achieved for 6,200 PV capacity with 43.78% cost increment.

4.4.1.5 Graphical Comparison of the Results for Tests 1 to 4

In this section, the results of the first group tests are summarized and compared in both graphical and tabular forms. Graphical results are given in Figures 4.2, 4.3, 4.4 and 4.5. In Figure 4.2, the daily 24 hour total electricity generation costs for varying PV capacities in Tests 1 to 4 – Case 1 are given. In Figure 4.3, the daily 24 hour total amount of curtailed PV energies for varying PV capacities in Tests 1 to 4 – Case 1 are given. Figures 4.4 and 4.5 provide the results for Case 2 and have the same scope with Figures 4.2 and 4.3, respectively.

As the PV capacity increases, the total daily electricity production cost decreases in B1 and B2 for all tests; and in the presence of curtailment penalty price, the cost starts increasing from the capacities that curtailment occurs as seen in Figure 4.2 as expected.

The curtailed PV energies in Test 2 are highly reduced as seen in Figure 4.3 compared with Test 1 since the bus selection is made considering the transmission line capacity and the closeness to loads. The less curtailed energies yield more PV generation and reduce the cost.

In Test 3, the maximum PV capacity with zero curtailment for B1 is 2,000 MW, for C1 it is 2,625 MW; for B2 it is 1,500 MW, and for C2 it is 2,125 MW. These results show that having dispersed PV generation (in comparison with Tests 1 and 2) can increase the PV capacity connected to the grid with zero curtailment.

In Test 2, the minimal costs are achieved for 2,025 MW and 1,800 MW PV capacities for C1 and C2, respectively. The minimal cost in Test 3 occurs for 2,750 MW PV capacity in C1 and 2,125 MW PV capacity in C2. It is concluded that dispersed PV generation can increase the total PV capacity which minimizes the total cost in the presence of curtailment penalty price. This is so, because more number of transmission lines are utilized by PVs and the local congestions are decreased compared with Test 2.

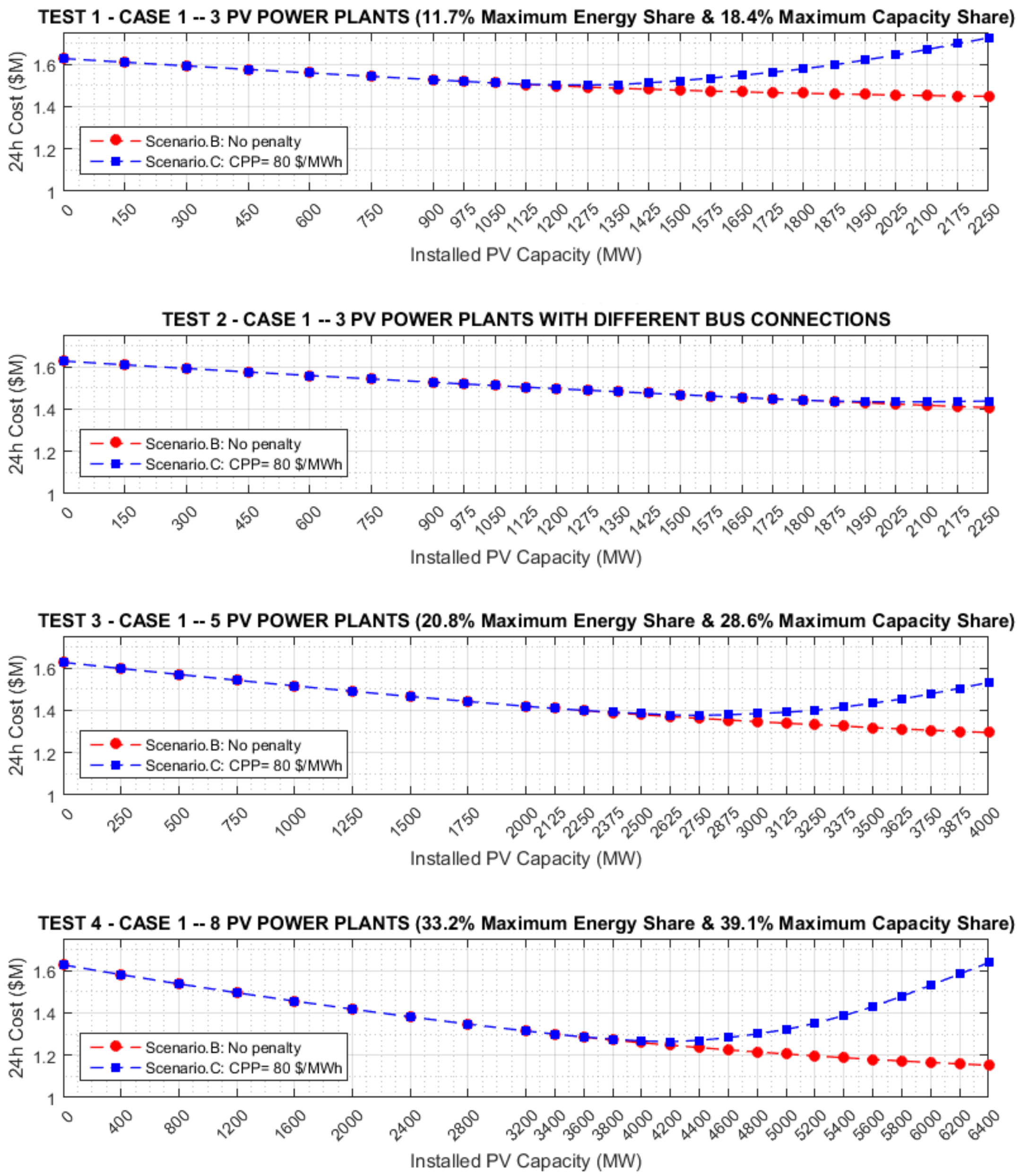

Figure 4.2 The daily 24 hours total electricity generation costs for varying PV capacities in Tests 1 to 4 – Case 1.

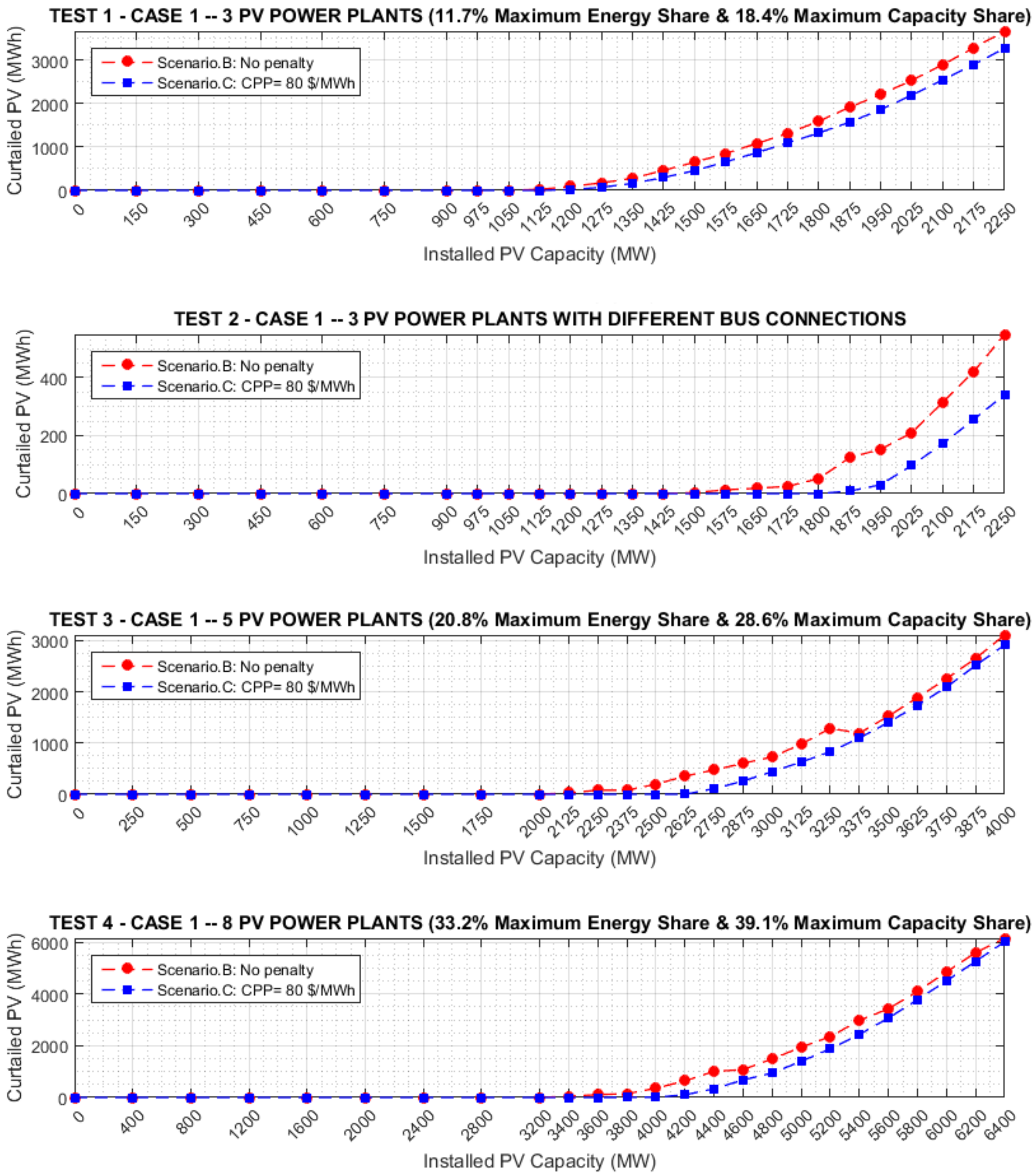

Figure 4.3 The daily 24 hours total amount of curtailed PV energies for varying PV capacities in Tests 1 to 4 – Case 1.

The minimal costs in Test 4 occur at 4,200 MW for C1 and 2,000 MW for C2, respectively. For C1, the PV capacity that gives the minimal cost increases from 2,750 MW to 4,200 MW compared with Test 3.

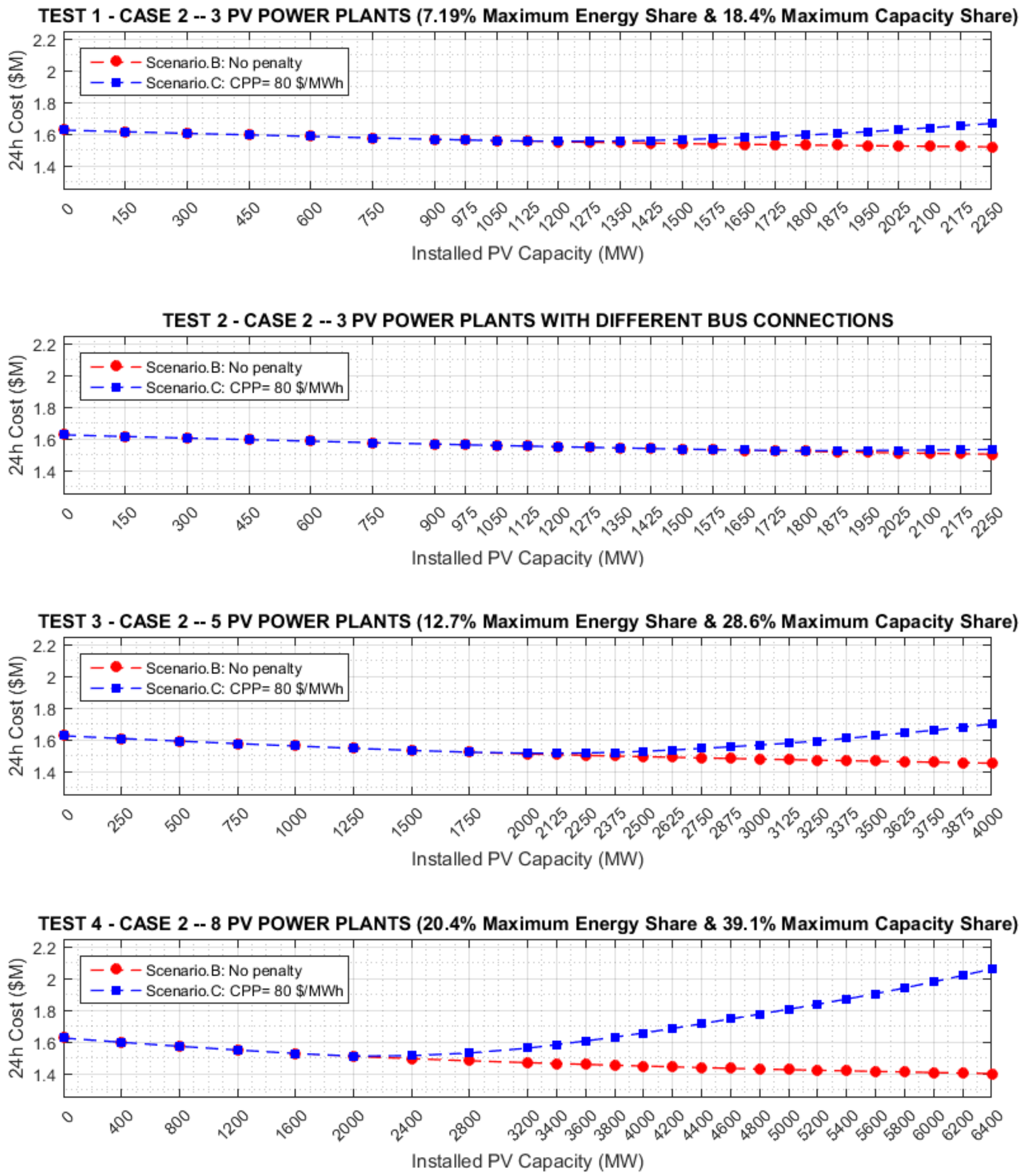

Figure 4.4 The daily 24 hours total electricity generation costs for varying PV capacities in Tests 1 to 4 – Case 2.

Although the number of PV generators is increased, in Test 4 the PV capacity that gives minimal cost in C2 does not increase because of the intermittency of PV generators. Sudden variations in PV generation are reached to a level that cannot be compensated because of ramp rate constraints of generators and congestions on transmission lines which prevent committing more number of generators to compensate the variations. However, in C2, the cost value for 2,000 MW capacity in Test 4 is less than the value in Test 3 since dispersing PV generation helps to reduce the curtailment and the resulting cost for more PV penetration levels as seen from Tables 4.9 and 4.7.

The curtailment penalty price reduces the curtailment with very small increments on the cost and enables large capacities of PVs to be connected to the system, which can be evaluated by checking the increments on costs and the reductions in curtailed energies from Figures 4.2 and 4.3 for Case 1, and from Figures 4.4 and 4.5 for Case 2.

Comparing Figures 4.3 and 4.5, it is observed that the CPP reduced more amounts of PV curtailment in Case 2 compared with Case 1 in each test. This situation is the result of intermittency of PV generation since it requires more number of generators or generators that are more expensive to be committed. Since the total daily PV generations are less in Case 2 compared with Case 1, the requirement of transmission line capacity decreases and the technical constraints of conventional generators become the main limitations that effect the utilization of PVs. Therefore, the CPP is more effective when the PV generation is intermittent since committing more number of generators or expensive generators yields additional costs.

In order to analyze the effect of dispersing PV capacity and CPP on the reduction of PV curtailment in detail, Tables 4.10 and 4.11 which show the curtailed energies for the same PV penetration levels in Tests 2, 3 and 4 are obtained by the help of Tables 4.4 to 4.9.

It is observed that having the same PV capacity with more number of power plants, the curtailment reduces in Case 1. In Case 2, the reduction is very low compared with Case 1 which is the result of ramp rates, and minimum up and down time constraints of generators. The CPP yields more curtailment reductions with less cost increments for the same PV capacities as the number of PV power plants increases in both cases. In addition, for the same PV capacities in both cases, the costs decrease as the dispersion of PV capacities increases from Tests 2 to 4.

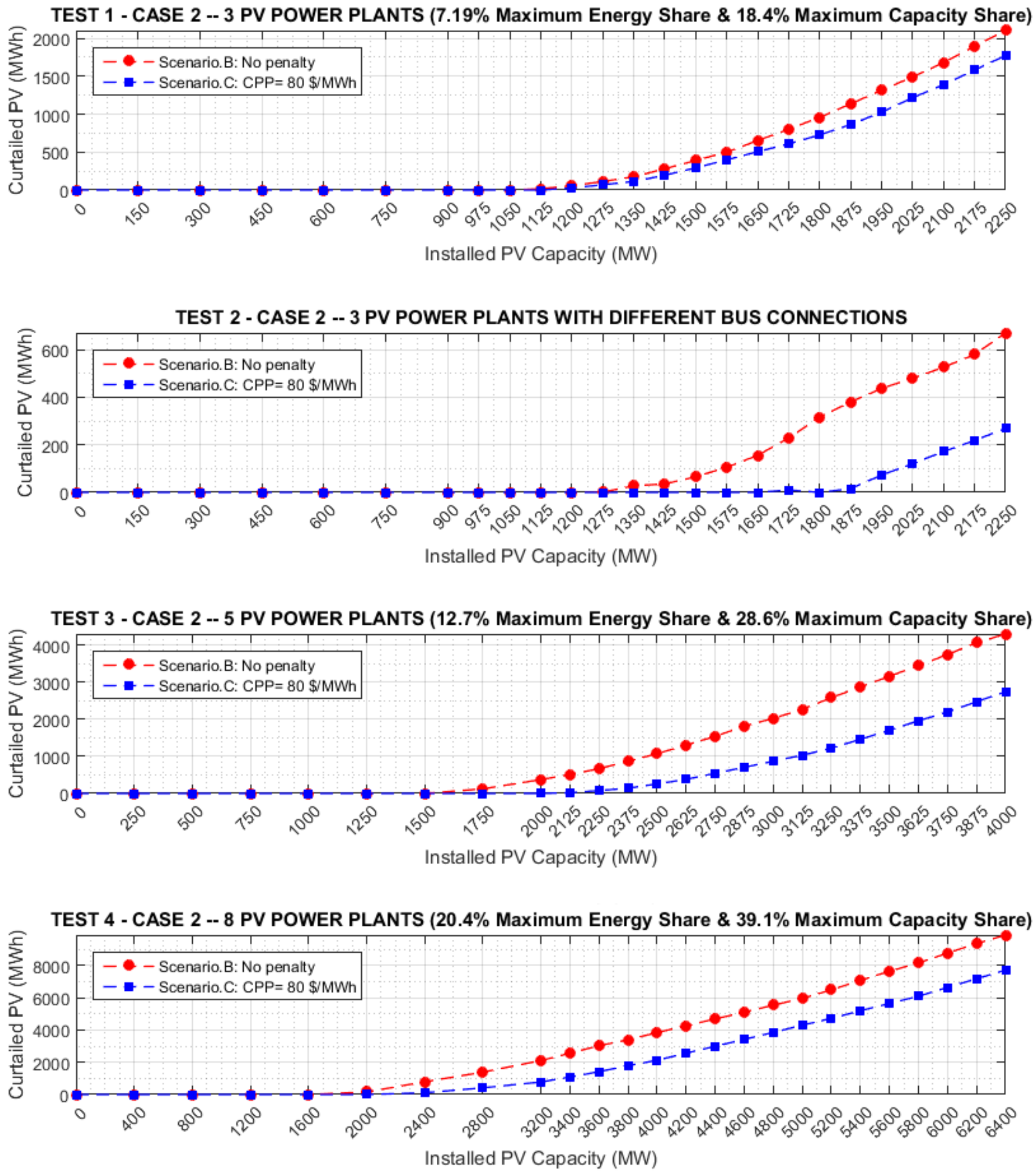

Figure 4.5 The daily 24 hours total amount of curtailed PV energies for varying PV capacities in Tests 1 to 4 – Case 2.

In all tests, the costs for the same PV capacity values in Case 2 are more compared with Case 1. This is expected because the available PV energy is low and there are more curtailments in Case 2.

Table 4.10 Curtailment and cost amounts for the same PV capacities in Tests 2, 3 and 4 – Case 1.

Analysis (Case 1)	Total PV Capacity (MW)	Total Curtailment (Sc. B) (MWh)	Total Curtailment (Sc. C) (MWh)	Curtailment Reduction (%)	Total Cost (Sc. C) ($)	Cost Increment (%)
Test 2	2,250	549	341	37.89	1,436,881	2.17
Test 3	2,250	80	0	100	1,399,250	0.09
Test 3	4,000	3,110	2,917	6.21	1,530,951	18.24
Test 4	4,000	357	9	97.48	1,266,270	0.64

Table 4.11 Curtailment and cost amounts for the same PV capacities in Tests 2, 3 and 4 – Case 2.

Analysis (Case 2)	Total PV Capacity (MW)	Total Curtailment (Sc. B) (MWh)	Total Curtailment (Sc. C) (MWh)	Curtailment Reduction (%)	Total Cost (Sc. C) ($)	Cost Increment (%)
Test 2	2,250	670	269	59.85	1,534,702	2.01
Test 3	2,250	667	78	88.31	1,518,358	1.03
Test 3	4,000	4,294	2,740	36.19	1,700,962	16.99
Test 4	4,000	3,834	2,121	44.68	1,657,860	14.37

The results obtained from Tests 1, 2, 3 and 4 are compared in the scope of PV capacity that yields the lowest cost and given in Table 4.12.

In Table 4.12, the minimal costs occur at the maximum PV capacities in B1 and B2 for all tests as expected. However, having these much of PV capacities may not be economically feasible in practice. The curtailed amount of available PV energy may prevent having more PV penetration levels because of increasing profit losses of PV generator companies as the PV penetration level increases.

The curtailment penalty price (Scenario C in Tests 1 to 4 – 80 $/MWh, the highest offer from generators) reduces the curtailed energy and enables higher capacities of PV generation with an acceptable increment on the cost. The curtailment penalty price is more effective in Case 2 since the curtailment reduction is more compared with Case 1.

Table 4.12 Summary of the results for Tests 1 to 4 (without PV, the total cost is 1.626 $M).

	Test 1				Test 2				Test 3				Test 4			
	Case 1		Case 2		Case 1		Case 2		Case 1		Case 2		Case 1		Case 2	
	Sc.B	Sc.C	Sc.B	Sc.C	Sc.B	Sc.C	Sc.B	Sc.C	Sc.B	Sc.C	Sc.B	Sc.C	Sc.B	Sc.C	Sc.B	Sc.C
Lowest Cost (LC) ($M)	1.448	1.501	1.521	1.557	1.406	1.434	1.504	1.526	1.295	1.376	1.454	1.516	1.152	1.264	1.402	1.512
PV Capacity at LC (MW)	2250	1275	2250	1350	2250	2100	2250	1875	4000	2750	4000	2125	6400	4200	6400	2000
Curtailment at LC (MWh)	3671	71	2103	113	549	171	670	15	3110	108	4294	19	6161	104	9872	1

As the PV capacity and dispersion of PV generators increase from Tests 1 to 4, the total cost reduces in both cases and both scenarios. In addition, the difference between the PV capacities for the lowest costs in Case 1 and Case 2 gets large as the PV capacity and the number of PV power plants increase from Tests 1 to 4 as well.

The maximum PV capacities with zero curtailment increase with small cost increments by using CPP in Tests 1 to 4. The maximum PV capacities with zero curtailment and corresponding cost increments from B1 to C1 and B2 to C2 for Tests 1 to 4 are given in Table 4.13.

Table 4.13 Change of maximum PV capacities with zero curtailment by CPP in Tests 1 to 4.

	Test 1				Test 2				Test 3				Test 4			
	Case 1		Case 2		Case 1		Case 2		Case 1		Case 2		Case 1		Case 2	
	Sc. B	Sc. C	Sc. B	Sc. C	Sc. B	Sc. C	Sc. B	Sc. C	Sc. B	Sc. C	Sc. B	Sc. C	Sc. B	Sc. C	Sc. B	Sc. C
Max. PV Capacity with Zero Curt. (MW)	1050	1125	1050	1125	1425	1800	1200	1800	2000	2625	1500	1750	3200	3600	1600	1600
Cost Change Between Sc. B and Sc. C by CPP (%)	-0.40		-0.21		-2.23		-1.64		-2.91		-0.73		-2.16		0	

By using the CPP, the maximum PV capacities with zero curtailment are increasing in C1 and C2 compared with B1 and B2, respectively. In addition, the costs are decreasing since the curtailments are zero and the PV capacities, as being cheap generation, are increasing. In Test 4, the maximum PV capacity with zero curtailment in C2 does not increase as in other tests since the ramping constraints of conventional generators and the capacities of transmission lines are becoming the main constraint while the PV capacity increases and results in more intermittency.

4.4.2 Group 2

4.4.2.1 Test 5: Eight PV Power Plants with Lower Curtailment Penalty Price

The scope of this test is the same with Test 4. The difference is in the value of curtailment penalty price. The CPP in Test 4 is 80 \$/MWh which is equal to the maximum price offered from generators. With this test, the effect of lower CPP, 40 \$/MWh, on total costs and amount of curtailed PV generations for different PV penetration levels are examined.

In this test, there are 2 different SCUC analyses consisting of C1 and C2 which are conducted for 24 different PV capacities making 48 daily SCUC analyses totally. The results of B1 and B2 are taken from Test 4 to obtain the tabular and graphical results.

4.4.2.2 Test 6: Eight PV Power Plants with Greater Curtailment Penalty Price

The scope of this test is also the same with Test 5. Only difference is in the curtailment penalty price. With this test, the effect of greater CPP, 160 $/MWh, on total costs and PV curtailments for different PV penetration levels are examined.

In this test, there are 48 daily SCUC analyses totally as in Test 5.

4.4.2.3 Test 7: Eight PV Power Plants with Huge Curtailment Penalty Price

This test has also the same scope with Test 5 but the CPP is increased to 320 $/MWh. With this test, the effect of huge CPP on total costs and PV curtailments for different PV penetration levels are examined.

There are also 48 daily SCUC analyses totally as in Test 5.

The results of Tests 4 to 7 are combined and given in Tables 4.14 to 4.17. The reductions in curtailed energy by CPP for different PV penetration levels in Tests 4 to 7 – Case 1 are given in Table 4.14. The cost increments by CPP for different PV penetration levels in Tests 4 to 7 – Case 1 are given in Table 4.15. Tables 4.16 and 4.17 provide the results for Case 2 and are in the same scope with Tables 4.14 and 4.15, respectively.

Table 4.14 The effects of curtailment penalty price on curtailed energies in Tests 4, 5, 6 and 7 - Case 1.

Tot. PV Cap. (MW)	*Tot. Curt. (T4-Sc. B) (MWh)*	*Tot. Curt. (T4-Sc. C) (MWh)*	*Tot. Curt. (T5) (MWh)*	*Tot. Curt. (T6) (MWh)*	*Tot. Curt. (T7) (MWh)*	*Curt. Reduction (T4-Sc. C) (%)*	*Curt. Reduction (T5) (%)*	*Curt. Reduction (T6) (%)*	*Curt. Reduction (T7) (%)*
400	0	0	0	0	0	-	-	-	-
800	0	0	0	0	0	-	-	-	-
1200	0	0	0	0	0	-	-	-	-
1600	0	0	0	0	0	-	-	-	-
2000	0	0	0	0	0	-	-	-	-
2400	0	0	0	0	0	-	-	-	-
2800	0	0	0	0	0	-	-	-	-
3200	0	0	0	0	0	-	-	-	-
3400	45	0	0	0	0	100	100	100	100
3600	111	0	0	0	0	100	100	100	100
3800	144	6	34	1	1	96	76	99	99
4000	357	9	39	9	0	97	89	97	100
4200	641	103	173	87	86	84	73	86	87
4400	1012	334	386	304	279	67	62	70	72
4600	1075	678	679	584	579	37	37	46	46
4800	1491	947	997	944	944	36	33	37	37
5000	1946	1394	1396	1380	1370	28	28	29	30
5200	2352	1888	1892	1876	1861	20	20	20	21
5400	2980	2432	2462	2428	2423	18	17	19	19
5600	3433	3074	3098	3053	3050	10	10	11	11
5800	4100	3780	3815	3747	3744	8	7	9	9
6000	4858	4511	4550	4494	4485	7	6	7	8
6200	5602	5267	5304	5248	5241	6	5	6	6
6400	6161	6023	6051	5998	5995	2	2	3	3

In Test 5 – C1, the percentages of curtailment reduction are slightly less than the percentages in Test 4 – C1. The curtailment reduction percentages for Tests 6 and 7 – C1 are nearly the same and slightly more than the percentages for Test 4 – C1.

In Test 7 – C1, the higher CPP does not increase the curtailment reductions compared with Test 6 which shows that the limitations of transmission lines and/or constraints of generators (such as ramp rates and minimum up and down times) are reached.

Table 4.15 The effects of curtailment penalty price on total costs in Tests 4, 5, 6 and 7 - Case 1.

Tot. PV Cap. (MW)	*Total Cost (T4-Sc. B) ($)*	*Total Cost (T4-Sc. C) ($)*	*Tot. Cost (T5) ($)*	*Tot. Cost (T6) ($)*	*Tot. Cost (T7) ($)*	*Cost Increment (T4-Sc. C) (%)*	*Cost Increment (T5) (%)*	*Cost Increment (T6) (%)*	*Cost Increment (T7) (%)*
400	1,580,043	1,580,021	1,580,077	1,579,987	1,580,016	0	0	0	0
800	1,536,365	1,536,311	1,536,339	1,536,308	1,536,290	0	0	0	0
1200	1,494,614	1,494,548	1,494,548	1,494,614	1,494,631	0	0	0	0
1600	1,455,221	1,455,191	1,455,212	1,455,199	1,455,222	0	0	0	0
2000	1,417,161	1,417,162	1,417,159	1,417,158	1,417,195	0	0	0	0
2400	1,380,722	1,380,719	1,380,666	1,380,727	1,380,681	0	0	0	0
2800	1,346,398	1,346,422	1,346,444	1,346,398	1,346,438	0	0	0	0
3200	1,314,302	1,314,285	1,314,326	1,314,309	1,314,291	0	0	0	0
3400	1,299,248	1,299,207	1,299,287	1,299,291	1,299,238	0	0	0	0
3600	1,284,798	1,285,898	1,285,903	1,285,910	1,285,903	0	0	0	0
3800	1,271,129	1,275,605	1,274,620	1,275,920	1,276,089	0	0	0	0
4000	1,258,270	1,266,270	1,265,467	1,267,031	1,267,857	1	1	1	1
4200	1,246,651	1,263,578	1,258,777	1,271,531	1,285,376	1	1	2	3
4400	1,235,648	1,269,887	1,255,446	1,295,610	1,342,695	3	2	5	9
4600	1,224,831	1,282,584	1,255,396	1,332,857	1,425,571	5	2	9	16
4800	1,214,709	1,300,178	1,259,585	1,374,464	1,525,513	7	4	13	26
5000	1,205,311	1,321,061	1,265,256	1,432,270	1,651,564	10	5	19	37
5200	1,196,224	1,350,417	1,274,774	1,501,144	1,799,768	13	7	25	50
5400	1,187,867	1,386,622	1,288,591	1,580,829	1,968,796	17	8	33	66
5600	1,179,756	1,428,793	1,305,458	1,674,300	2,162,677	21	11	42	83
5800	1,172,356	1,477,843	1,326,146	1,778,769	2,377,988	26	13	52	103
6000	1,165,374	1,529,768	1,348,292	1,890,102	2,608,725	31	16	62	124
6200	1,158,652	1,582,978	1,371,473	2,003,773	2,842,722	37	18	73	145
6400	1,152,267	1,636,606	1,394,907	2,117,795	3,077,266	42	21	84	167

Inspecting the cost increment percentages in Table 4.15, it is observed that the percentages for Test 5 are less than the percentages for Test 4.

The curtailment reduction percentages for Tests 6 and 7 – C1 are nearly equal, and there are only small increments from the percentages for Test 4. The greater CPP of Tests 6 and 7 resulted dramatically more costs for nearly equal amounts of curtailed energy.

Table 4.16 The effects of curtailment penalty price on curtailed energies in Tests 4, 5, 6 and 7 - Case 2.

Tot. PV Cap. (MW)	*Tot. Curt. (T4-Sc. B) (MWh)*	*Tot. Curt. (T4-Sc. C) (MWh)*	*Tot. Curt. (T5) (MWh)*	*Tot. Curt. (T6) (MWh)*	*Tot. Curt. (T7) (MWh)*	*Curt. Reduction (T4-Sc. C) (%)*	*Curt. Reduction (T5) (%)*	*Curt. Reduction (T6) (%)*	*Curt. Reduction (T7) (%)*
400	0	0	0	0	0	-	-	-	-
800	0	0	0	0	0	-	-	-	-
1200	0	0	0	0	0	-	-	-	-
1600	0	0	0	0	0	-	-	-	-
2000	158	1	0	0	0	99	100	100	100
2400	788	109	147	77	77	86	81	90	90
2800	1385	413	441	381	381	70	68	72	72
3200	2102	776	909	686	686	63	57	67	67
3400	2557	1083	1271	993	992	58	50	61	61
3600	3022	1417	1642	1331	1325	53	46	56	56
3800	3390	1781	2022	1669	1657	47	40	51	51
4000	3834	2121	2402	2021	2021	45	37	47	47
4200	4257	2563	2810	2444	2444	40	34	43	43
4400	4679	2985	3259	2866	2866	36	30	39	39
4600	5092	3413	3703	3289	3287	33	27	35	35
4800	5532	3845	4135	3711	3711	30	25	33	33
5000	5954	4293	4573	4134	4134	28	23	31	31
5200	6480	4715	5048	4556	4556	27	22	30	30
5400	7069	5186	5485	5003	4979	27	22	29	30
5600	7628	5638	5998	5474	5401	26	21	28	29
5800	8146	6085	6471	5933	5890	25	21	27	28
6000	8761	6631	6936	6446	6425	24	21	26	27
6200	9351	7165	7442	6973	6967	23	20	25	25
6400	9872	7712	8004	7517	7515	22	19	24	24

The decrement in curtailment reduction percentages between Test 4 – C2 and Test 5 – C2 are more compared with Test 4 – C1 and Test 5 – C1 which shows that a lower CPP increases the curtailment when intermittency occurs in the PV generation.

The curtailment reduction percentages for Tests 6 and 7 – C2 are nearly equal and more than the values for Test 4 which show that a higher CPP can decrease the curtailment when intermittency occurs in the PV generation. However, since the percentages of curtailment reductions for Tests 6 and 7 – C2 are nearly the same, it is concluded that increasing the CPP after a level does not reduce the curtailment when the limitations of transmission lines and/or generators are reached.

The maximum reduction on curtailment in Case 1 by a greater CPP is observed approximately 100 MWh for 4,600 MW PV capacity in Test 7 – C1. In Case 2, more reductions on curtailment are observed in Tests 6 and 7 – C2 compared with Test 4 – C2 which also show that a greater CPP is more effective on reducing curtailment when PV has intermittent generation.

There are small differences in curtailment reduction percentages for Tests 4 and 5 – C2 as seen in Table 4.16, and since the CPP is lower in Test 5, the cost increment percentages for Test 5 are less than the percentages for Test 4 in Table 4.17.

Table 4.17 The effects of curtailment penalty price on total costs in Tests 4, 5, 6 and 7 - Case 2.

Tot. PV Cap. (MW)	*Total Cost (T4-Sc. B) ($)*	*Total Cost (T4-Sc. C) ($)*	*Tot. Cost (T5) ($)*	*Tot. Cost (T6) ($)*	*Tot. Cost (T7) ($)*	*Cost Increment (T4-Sc. C) (%)*	*Cost Increment (T5) (%)*	*Cost Increment (T6) (%)*	*Cost Increment (T7) (%)*
400	1,599,390	1,599,418	1,599,433	1,599,425	1,599,420	0	0	0	0
800	1,573,990	1,573,997	1,573,990	1,573,990	1,573,995	0	0	0	0
1200	1,550,532	1,550,517	1,550,539	1,550,584	1,550,513	0	0	0	0
1600	1,528,821	1,528,792	1,528,814	1,528,827	1,528,795	0	0	0	0
2000	1,510,513	1,511,922	1,511,917	1,511,906	1,511,918	0	0	0	0
2400	1,496,219	1,515,095	1,509,775	1,521,951	1,534,224	1	1	2	3
2800	1,482,554	1,531,703	1,514,617	1,562,991	1,624,027	3	2	5	10
3200	1,470,996	1,562,211	1,529,675	1,618,821	1,728,646	6	4	10	18
3400	1,465,520	1,584,443	1,538,861	1,666,449	1,825,191	8	5	14	25
3600	1,460,029	1,607,743	1,548,316	1,716,028	1,928,690	10	6	18	32
3800	1,454,751	1,631,749	1,558,201	1,767,732	2,033,816	12	7	22	40
4000	1,449,558	1,657,860	1,569,413	1,823,272	2,146,661	14	8	26	48
4200	1,444,559	1,686,554	1,581,408	1,884,989	2,275,947	17	9	30	58
4400	1,439,695	1,716,340	1,593,509	1,948,885	2,407,459	19	11	35	67
4600	1,435,119	1,746,378	1,606,068	2,012,871	2,539,307	22	12	40	77
4800	1,430,772	1,776,726	1,618,744	2,077,079	2,670,873	24	13	45	87
5000	1,426,722	1,807,195	1,631,772	2,142,074	2,803,728	27	14	50	97
5200	1,422,983	1,838,692	1,645,297	2,209,413	2,938,386	29	16	55	106
5400	1,419,350	1,871,584	1,659,957	2,278,097	3,075,188	32	17	61	117
5600	1,415,820	1,905,992	1,676,018	2,348,180	3,213,600	35	18	66	127
5800	1,412,241	1,941,854	1,692,851	2,421,074	3,364,810	38	20	71	138
6000	1,408,740	1,980,177	1,710,482	2,500,250	3,528,978	41	21	77	151
6200	1,405,250	2,020,523	1,729,102	2,583,517	3,698,477	44	23	84	163
6400	1,401,867	2,061,550	1,748,253	2,667,582	3,870,184	47	25	90	176

In Table 4.16, there are small increments in curtailment reduction percentages for Test 6 – C2 compared with Test 4 – C2. The CPP value is greater in Test 6 – C2, and the cost increment percentages for Test 6 – C2 are more compared with Test 4 – C2. Since the curtailment reduction percentages for Tests 6 and 7 – C2 are nearly equal and the CPP is greater in Test 7 – C2, the cost increment percentages for Test 7 – C2 are dramatically more compared with Tests 4, 5, and 6 – C2 as seen in Table 4.17.

4.4.2.4 Graphical Comparison of the Results for Tests 4 to 7

In this section, the results of the second group of tests are summarized and compared in both graphical and tabular forms. In Figure 4.6, the daily 24 hour total amount of curtailed PV energies for varying CPP and PV capacities in Tests 4 to 7 – Case 1 and Case 2 are given. In Figure 4.7, the daily 24 hour total electricity generation costs for varying CPP and PV capacities in Tests 4 to 7 – Case 1 and Case 2 are given.

When the CPP is reduced to 40 $/MWh in Test 5 – C1, the amounts of curtailed energy are nearly the same with Test 4 – C1. However, in Case 2, the curtailments in T5 – C2 are more compared with Test 4 – C2. Therefore, it can be said that greater CPP does not have dramatic effect on reducing curtailment when there is no intermittency in PV generation, and a lower CPP mostly affects Case 2 where the PV generation data has intermittency.

It is observed that the costs in both Case 1 and Case 2 for Tests 4 to 7 increase by increasing CPP while the PV penetration levels are increasing, as expected. Moreover, the cost increments in Case 2 are more since the PV generations are low and there are more curtailment compared with Case 1.

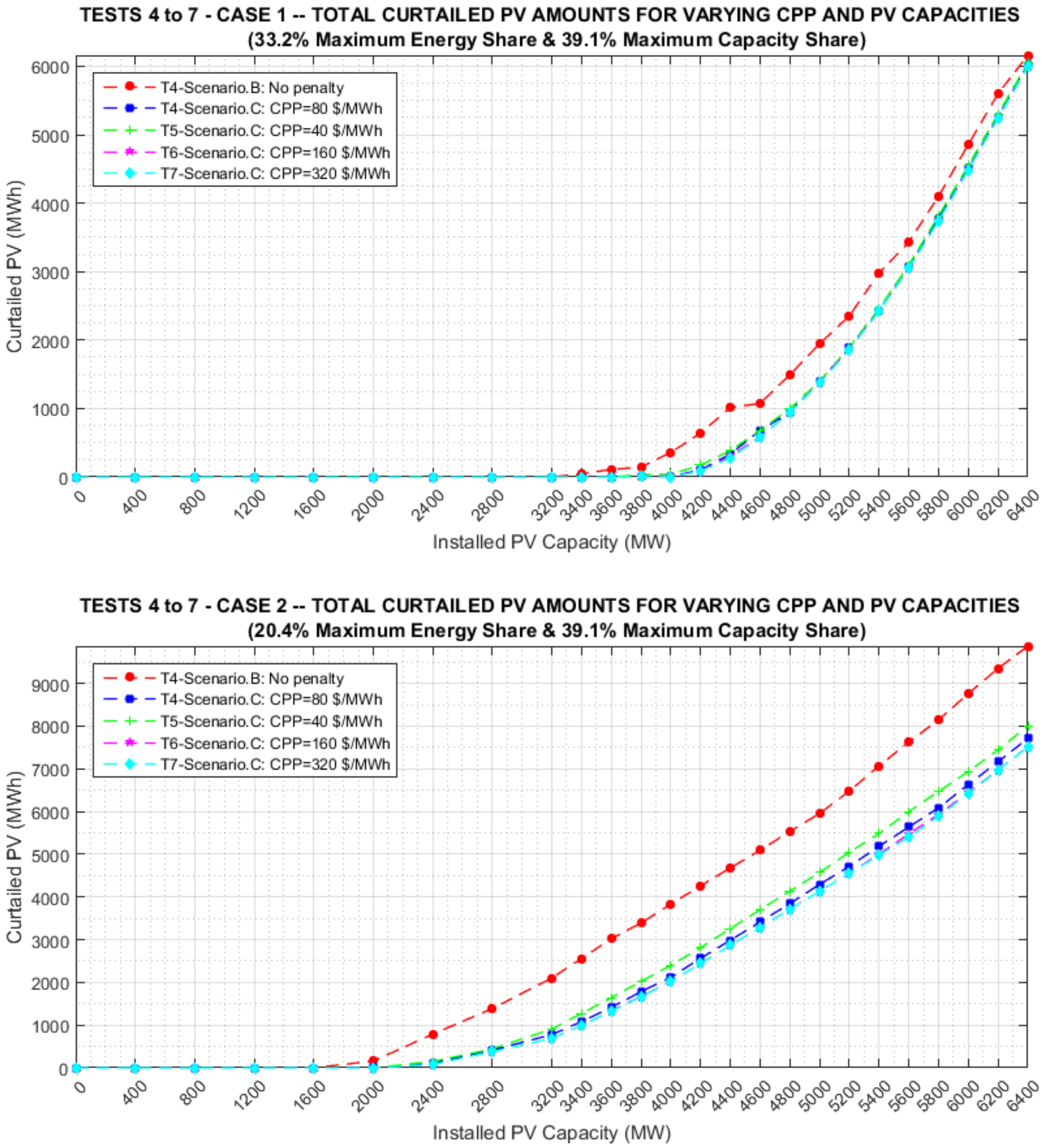

Figure 4.6 The daily 24 hours total amount of curtailed PV energies for varying CPP and PV capacities in Tests 4 to 7 – Case 1 and Case 2.

Since the curtailed energies for Test 5 – C1 and Test 4 – C1 are nearly the same and the total costs are slightly less in Test 5 – C1 compared with Test 4 – C1, it can be said that there is no need to increase the CPP for more curtailment reductions in Case 1.

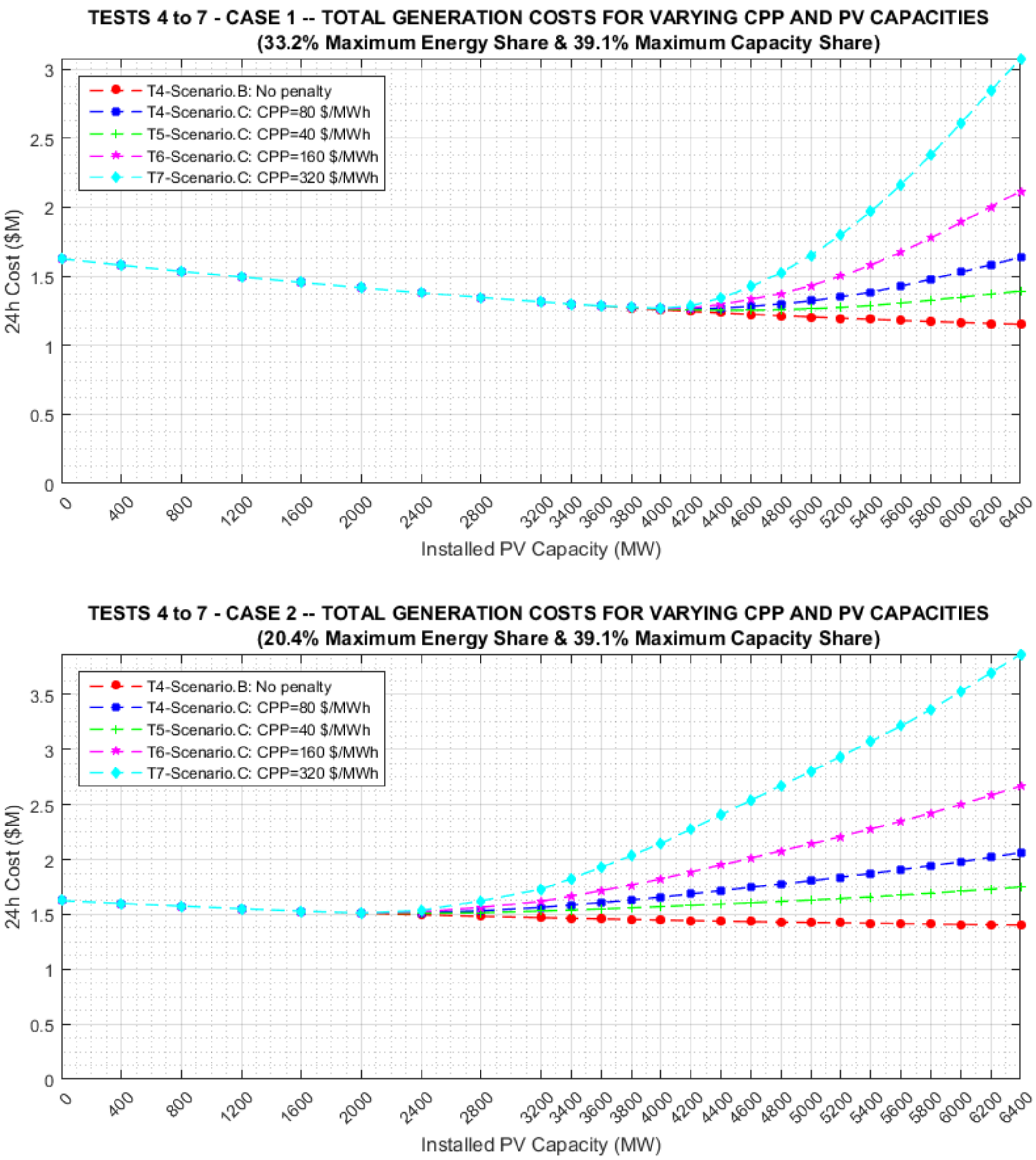

Figure 4.7 The daily 24 hours total electricity generation costs for varying CPP and PV capacities in Tests 4 to 7 – Case 1 and Case 2.

In Test 5 – C2, the costs are less compared with Test 4 – C2 since there is no dramatic increment on the curtailed energies and the CPP is lower.

In Test 6 – C1, the curtailed energies are nearly the same with Test 4 – C1. However, the costs increase dramatically compared with Tests 4 and 5 – C1 since the CPP is increased to 160 $/MWh.

In Test 6 – C2, there are small decrements in curtailed energy compared with Test 4 – C2, but since the CPP is increased the total costs increase dramatically compared with Test 4 – C2 with the increasing total PV capacity.

In Test 7 – C1 and C2, the curtailed energies of PV energy are nearly the same with the values in Test 6. However, the costs are more compared with Test 6 since the CPP is greater.

The results obtained from Tests 4, 5, 6 and 7 are compared in the scope of PV capacity that yields the lowest cost and are given in Table 4.18.

It is seen that when the CPP is reduced to 40 $/MWh, the lowest cost in Test 4 – C1 is reduced and the PV capacity at this cost increases to 4,600 MW. Although the curtailment is more in Test 5 – C1 compared with Test 4 – C1, the amount of total daily PV generation is more than Test 4 due to the increment in PV capacity. The same situation also occurs in Test 5 – C2 compared with Test 4 – C2 since the PV capacity at the lowest cost increases to 2,400 MW which yields more daily PV generation.

Tests 6 and 7 have the same PV capacities at the lowest costs and almost the same lowest costs in both Case 1 and Case 2. Increasing the CPP does not make dramatic effect on PV capacity that yields minimal cost in Tests 6 and 7. What is more, having a lower CPP is better as in Test 5 for having the lowest costs both in C1 and C2 compared with Tests 4, 6 and 7 since the PV capacity amounts at lowest cost and the corresponding total daily PV generations are more in Test 5 – C1 and C2 compared with Tests 4, 6 and 7.

Table 4.18 Summary of the results for Tests 4 to 7.

	Test 4 (CPP=80 $/MWh)		Test 5 (CPP=40 $/MWh)		Test 6 (CPP=160 $/MWh)		Test 7 (CPP=320 $/MWh)	
	Case 1	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**
	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C
Lowest Cost (LC) ($M)	1.264	1.512	1.255	1.51	1.267	1.512	1.268	1.512
PV Capacity at LC (MW)	4200	2000	4600	2400	4000	2000	4000	2000
Curtailment at LC (MWh)	103	1.13	679	146	9	0	0	0
Total Daily PV Generation at LC (MWh)	29,310	8331	31,530	9851	28,000	8332	28,010	8332

The maximum PV capacity amounts with zero curtailment and corresponding cost increments from B1 to C1 and B2 to C2 for Tests 4 to 7 are given in Table 4.19.

The decreasing costs in Test 4 – C1 and in Tests 5 to 7 – C1 and C2 are result of the increased PV generation capacities with zero curtailment since the PV generation is cheap compared with conventional generators. There is 400 MW increment from 3,600 MW to 4,000 MW PV capacity with zero curtailment in Test 7 – C1 compared with Test 4 – C1. The curtailed energy for 4,000 MW PV capacity in Tests 4, 5 and 6 – C1 are 9, 39 and 9 MWh, respectively, as seen in Table 4.14. These amounts are significantly low and ignorable compared with 4,000 MW PV capacity, and the increment in PV capacity with zero curtailment is ignorable. There are also 400 MW increment from 1,600 MW to 2,000 MW PV capacity with zero curtailment in Tests 5 to 7 – C2 compared with Test 4 – C2. However, since the curtailed energy for 2,000 MW PV capacity in Test 4 – C2 is only 1 MWh as seen in Table 4.16, the increment in PV capacity with zero curtailment is also ignorable.

It is observed that changing the CPP does not have a dramatic effect on increasing the PV capacity with zero curtailment since the ramping rates of generators and the transmission capacities limit the system flexibility that is required to handle the increasing intermittency for more PV capacities.

Table 4.19 Change of maximum PV capacities with zero curtailment by CPP in Tests 4 to 7.

	Test 4 (CPP=80 $/MWh)				Test 5 (CPP=40 $/MWh)		Test 6 (CPP=160 $/MWh)		Test 7 (CPP=320 $/MWh)	
	Case 1		Case 2		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
	Sc. B	Sc. C	Sc. B	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C	Sc. C
Max. PV Capacity with Zero Curt. (MW)	3200	3600	1600	1600	3600	2000	3600	2000	4000	2000
Cost Change Between Test 4 - Sc.B and Sc.C by CPP (%)	-2.16		0		-2.16	-1.11	-2.16	-1.11	-3.53	-1.11

As an overview, the SCUC algorithm is forced to find optimal generator schedule with total minimal cost by minimizing the PV curtailment, and it is observed that the curtailed amount of available PV generation is reduced with the existence of CPP in the objective function of SCUC algorithm.

The CPP reduced the curtailment with acceptable increments on the total cost up to some PV penetration levels. As the PV penetration levels are increasing, the percentages of curtailment reductions decrease because of the reserve requirements, minimum up and minimum down times, and ramp rate constraints of generators and transmission line limitations of the network. This situation is prevented by dispersing PV generations into more number of connection buses and more reductions of curtailments are observed for the same PV capacities.

Since a higher CPP has more effect on reducing the curtailment of PV energy when the PV generation is intermittent compared with average generation, the optimal CPP can be determined by utilizing the density of occurrence of intermittency for the corresponding place. In addition, the maximum total PV capacity should be determined by analyzing the effect of PV penetration level on the SCUC to check the economic feasibility considering curtailments.

CHAPTER 5

CONCLUSIONS

In this thesis study, the effect of PV penetration level on Security Constrained Unit Commitment is evaluated with the motivation of increasing interest on PV energy and the RES energy targets for the future. The technical characteristics of PV generators are integrated to the SCUC algorithm.

Recalling that the cost constraints of generators have start up and shut down costs, operational costs and technical constraints as minimum up and down times, ramp rates, minimum generation limits and system constraints as reserve requirements and transmission line limits, the technical constraints of conventional generators and system constraints yield curtailment of PV energy in SCUC schedules because of requiring commitment of more number of generators or more expensive generators which may result more cost compared to the case without PV. The curtailment of available PV energy can be reduced by introducing CPP and adding it as an additional constraint into the SCUC algorithm. The CPP forces the SCUC algorithm to minimize the curtailment by bringing extra cost for existence of curtailment which becomes effective when the curtailment cost is more than the additional costs of required commitments of more number of generators or more expensive generators.

For simulations, 529 different daily SCUC analyses including two scenarios and two cases under seven different tests are conducted on the IEEE 118 Bus Test System. 385 analyses are conducted for different size and number of PV power plants that are connected to the test system from different bus combinations for Tests 1, 2, 3 and 4.

144 analyses are conducted within the same configuration as Test 4 but having different CPPs for Tests 5, 6 and 7.

It is observed that the increasing PV generation reduces the cost but the PV capacity can reach to a level that may not be economically feasible to implement because of the curtailment of available PV energy. The curtailment penalty price reduces the curtailed energy with very low increment in the cost which can enable higher capacities of PV energy to be injected to the grid within the constraints of generators and transmission system.

The percentages of curtailment reductions and corresponding cost increments from B1 to C1 and B2 to C2 validate the use of curtailment penalty price. For instance, the maximum installed PV capacity with zero curtailment increases with cost decrements by 375 MW, 625 MW and 400 MW in Tests 2, 3 and 4 – Case 1, respectively; 600 MW and 250 MW in Tests 2 and 3 – Case 2, respectively. Moreover, reducing considerable amounts of PV curtailments with acceptable increments on costs also validate the use of CPP. For example, 354 MWh, 503 MWh and 921 MWh curtailed PV energies are eliminated with 0.54%, 0.59% and 3.10% cost increments in Test 3 - Case 1 and Case 2, respectively. By changing the CPP, the relation between the curtailed energies and the CPP is examined, and it is observed that the higher CPPs are mostly effective when the PV generation data has intermittent characteristics.

In conclusion, the inclusion of CPP is observed to be a method to increase the utilization of PVs with low increments on the cost that can be applied by system operators before upgrading the capacities of transmission lines and forcing conventional generators to be fast responsive considering the technical constraints.

The modified SCUC algorithm is modular and parametric. It can be adopted to any transmission grid. For the system operators, it can provide valuable insight concerning the impact of large capacities of PV power plants to unit commitment and enabling higher capacities of PV power plants for increasing RES ratio in electricity generation by making them economically feasible.

As the future studies, Monte Carlo method can be used to create estimations for PV generation data by help of the past measured values and more accurate SCUC analyses can be made. Moreover, Probability Density Function (PDF) of PV generation characteristics can be utilized for creating data of daily PV generation considering the density of intermittency occurrence. A yearly SCUC analysis of the IEEE 118 Bus Test System or any transmission grid including PV power plants with different penetration levels can be conducted by varying the CPP, by using the generated or real data of PVs in order to examine the effect of CPP to the yearly cost considering intermittency. This yearly SCUC analysis can be used to optimize the CPP. In addition, the CPP can be integrated to stochastic SCUC algorithms as a dynamic constraint (or hourly dynamic constraint) and optimal CPP can be determined for different or desired PV penetration levels by considering the intensity of PV intermittency and load variations in one complete SCUC problem.

REFERENCES

[1] International Energy Agency (IEA), "Key World Energy Statistics 2014," [Online]. Available: http://www.iea.org/publications/freepublications/ publication/keyworld2014.pdf. [Accessed: Au. 25, 2015].

[2] Eurostat, “Share of renewables in energy consumption up to 15% in the EU in 2013,” [Online]. Available: http://ec.europa.eu/eurostat/documents/ 2995521/6734513/8-10032015-AP-EN.pdf/3a8c018d-3d9f-4f1d-95ad-832ed3a20a6b. [Accessed: May 20, 2015].

[3] California Independent System Operator (ISO), “California Renewables Portfolio Standard (RPS),” [Online]. Available: http://www.cpuc.ca.gov/ PUC/energy/Renewables/. [Accessed: Ap. 15, 2015].

[4] Daneshi, H.; Srivastava, A.K., "Security-constrained unit commitment with wind generation and compressed air energy storage," Generation, Transmission & Distribution, IET , vol.6, no.2, pp.167,175, February 2012

[5] Daneshi, H.; Srivastava, A.K.; Daneshi, A., "Security constrained unit commitment with phase shifter and wind generation," Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1,7, 24-29 July 2011

[6] Vergnol, A.; Rious, V.; Sprooten, J.; Robyns, B.; Deuse, J., "Integration of renewable energy in the European power grid: Market mechanism for congestion management," Energy Market (EEM), 2010 7th International Conference on the European , vol., no., pp.1,6, 23-25 June 2010

[7] Hongyu Wu; Shahidehpour, M., "Stochastic SCUC Solution With Variable Wind Energy Using Constrained Ordinal Optimization," Sustainable Energy, IEEE Transactions on , vol.5, no.2, pp.379,388, April 2014

[8] Restrepo, J.F.; Galiana, F.D., "Assessing the Yearly Impact of Wind Power Through a New Hybrid Deterministic/Stochastic Unit Commitment," Power Systems, IEEE Transactions on , vol.26, no.1, pp.401,410, Feb. 2011

[9] U.S. Energy Information Administration, "U.S. Energy Consumption By Energy Source, 2014" [Online]. Available: http://www.eia.gov/energyexplained/index.cfm?page=renewable_home. [Accessed: Jun. 11, 2015].

[10] Federal Energy Regulatory Commission (FERC), "MISO's Existing Methods for Managing Voltage and Plans to Improve Voltage Profiles - Apr. 2012," [Online]. Available: http://www.ferc.gov/CalendarFiles/20120503131554-MISO.pdf. [Accessed: Jul. 20, 2015].

[11] Federal Energy Regulatory Commission (FERC), "Overcoming Computational Challenges on Large Scale Security Constrained Unit Commitment (SCUC) Problems – MISO and Alstom's Experience with MIP Solver – Jun. 2014," [Online]. Available: http://www.ferc.gov/CalendarFiles/20140623080505-M1%20-%201%20-%20FERC2014_Chen_M1_06172014.pdf . [Accessed: Jul. 20, 2015].

[12] New York Independent System Operator (NY ISO), "Day-Ahead Scheduling Manual," [Online]. Available: http://www.nyiso.com/public/webdocs/markets_operations/documents/Manuals_and_Guides/Manuals/Operations/day ahd_schd_mnl.pdf. [Accessed: Jul. 21, 2015].

[13] California Independent System Operator (CaISO), "Market Optimization Details – Jun. 2009," [Online]. Available: http://www.caiso.com/23cf/23cfe2c91d880.pdf . [Accessed: Jul. 25, 2015].

[14] Global Wind Energy Council, "Global Wind Statistics 2014," [Online]. Available: http://www.gwec.net/wp-content/uploads/2015/02/GWEC_Global WindStats2014_FINAL_10.2.2015.pdf. [Accessed: Jun. 20, 2015].

[15] International Energy Agency (IEA), "Technology Roadmap: Solar Photovoltaic Energy – Oct. 2014," [Online]. Available: https://www.iea.org/publications/freepublications/publication/TechnologyRoad mapSolarPhotovoltaicEnergy_2014edition.pdf. [Accessed: May 25, 2015].

[16] Renewable Energy Policy Network for 21st Century (REN21), "Renewables 2015 Global Status Report – Sep. 2015," [Online]. Available:

http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_ Onlinebook_low1.pdf. [Accessed: Au. 20, 2015].

[17] U.S. Energy Information Administration, "International Energy Statistics," [Online]. Available: http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid= 2&pid=2&aid=7&cid=ww,&syid=2008&eyid=2012&unit=MK. [Accessed: Oct. 15, 2015].

[18] Renewable Energy Policy Network for 21st Century - REN21, "Renewables 2014 Global Status Report - Sep. 2014," [Online]. Available: http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_ KeyFindings_low%20res.pdf. [Accessed: May 28, 2015].

[19] Eurostat, "Share of energy from renewable sources," [Online]. Available: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ind_335a&lang= en. [Accessed: Ap. 15, 2015].

[20] California ISO, "Daily Renewables Watch," [Online]. Available: http://www.caiso.com/green/renewableswatch.html. [Accessed: Ap. 15, 2015].

[21] Fraunhofer ISE, "Recent Facts about Photovoltaics in Germany," [Online]. Available: https://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/recent-facts-about-photovoltaics-in-germany.pdf. [Accessed: Oct. 20, 2015].

[22] EPIA – European Photovoltaic Industry Association, "Global Market Outlook for Photovoltaics 2014-2018 – June 2014," [Online]. Available: http://www.kigeit.org.pl/FTP/PRCIP/Literatura/093_EPIA_Global_Market_ Outlook_for_Photovoltaics_2014-2018.pdf. [Accessed: Ap. 20, 2015].

[23] International Energy Agency (IEA), "Snapshot of Global PV Markets 2014," [Online]. Available: http://helapco.gr/pdf/PVPS_report_-_A_Snapshot_of_ Global_PV_-_1992-2014.pdf. [Accessed: May. 19, 2015].

[24] Greentech Media, "Solar Star, Largest PV Power Plant in the World, Now Operational," [Online]. Available: http://www.greentechmedia.com/articles/ read/Solar-Star-Largest-PV-Power-Plant-in-the-World-Now-Operational. [Accessed: Jul. 20, 2015].

[25] Simsek, B.; Bizkevelci, E., "Türkiye Elektrik Dağitim Şebekesinde Fotovoltaik Sistemlerin Güç Kalitesine Etkisi," in IV. Elektrik Tesisat Ulusal Kongre ve Sergisi, Izmir, EMO, 21 Oct. 2015

[26] Republic of Turkey Ministry of Energy and Natural Resources, "Elektrik enerjisi piyasası ve arz güvenliği stratejisi belgesi," [Online]. Available: http://www.enerji.gov.tr/File/?path=ROOT%2F1%2FDocuments%2FBelge%2FArz_Guvenligi_Strateji_Belgesi.pdf. [Accessed: Aug. 10, 2015].

[27] Republic of Turkey Ministry of Energy and Natural Resources, "National Renewable Energy Action Plan for Turkey, 2014," [Online]. Available: http://www.eie.gov.tr/duyurular_haberler/document/National_Renewable_Energy_Action_For_Turkey.PDF. [Accessed: Sep 4, 2015].

[28] Fraunhofer ISE, "Current Status of Concentrator Photovoltaic (CPV) Technology," [Online]. Available: https://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/current-status-of-concentrator-photovoltaic-cpv-technology.pdf. [Accessed: Sep 20, 2015].

[29] Newquay Weather Station, "Solar PV – 2014 Generation, Data of 05 December 2014," [Online]. Available: http://www.newquayweather.com/wxsolarpv2014.php. [Accessed: Au. 15, 2015].

[30] M. Shahidehpour, Hatim Yamin and Zuyi Li, Market Operations in Electric Power Systems, 1st ed. New York: Wiley, 2002.

[31] KU Leuven Energy Institute – TME Branch, "DC Power Flow in Unit Commitment Models," [Online]. Available: https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wpen2014-12.pdf. [Accessed: May 10, 2015].

[32] Yu, N.P.; Sheng, H.Y.; Johnson, R., "Economic valuation of wind curtailment rights," Power and Energy Society General Meeting (PES), 2013 IEEE , vol., no., pp.1,5, 21-25 July 2013

[33] National Renewable Energy Laboratory – NREL, "Wind and Solar Energy Curtailment: Experience and Practices in the United States – Mar. 2014,"

[Online]. Available: http://www.nrel.gov/docs/fy14osti/60983.pdf. [Accessed: Sep. 15, 2015].

[34] Burke, D.J.; O'Malley, M.J., "Factors Influencing Wind Energy Curtailment," in Sustainable Energy, IEEE Transactions on , vol.2, no.2, pp.185-193, April 2011

[35] National Renewable Energy Laboratory – NREL, "Wind and Solar Curtailment - Oct. 2013," [Online]. Available: http://www.nrel.gov/docs/fy13osti/60245.pdf. [Accessed: Sep. 20, 2015].

[36] National Renewable Energy Laboratory – NREL, "Examples of Wind Energy Curtailment Practices - Jul. 2010," [Online]. Available: http://www.nrel.gov/docs/fy10osti/48737.pdf. [Accessed: Sep. 18, 2015].

[37] Fan Xu; Ying Wang; Qia Ding; Kaifeng Zhang, "Optimization of wind power integration considering security constraints," in Power System Technology (POWERCON), 2014 International Conference on , vol., no., pp.2573-2579, 20-22 Oct. 2014

[38] Illinois Institute of Technology, "IEEE 118 Bus Test System Data," [Online]. Available: http://motor.ece.iit.edu/data/. [Accessed: Oct. 01, 2014].

APPENDIX A

SUMMARY OF THE SCUC ALGORITHM

In this appendix, the summary of the SCUC algorithm is given. The following notations are used to formulate the constraints and the objective function [30].

Index:

i	Unit index,
t	Hour index,
NH	Number of hours,
NB	Number of buses,
m	Segment index for a piecewise or stepwise cost curve.

Variables:

u_{it}	Unit status indicator (binary, 1 means unit i is ON at hour t),
y_{it}	Start up indicator (binary, 1 means unit i is started up at hour t),
z_{it}	Shut down indicator (binary, 1 means unit i is shut down at hour t),
p_{it}	Generation amount for unit i at hour t,
$px_{it,m}$	Generation amount for unit i at hour t at cost segment m,
$\delta_{it,m}$	Commitment indicator for unit i at hour t at cost segment m,
sr_{it}	Spinning reserve for unit i at hour t,
or_{it}	Operating reserve for unit i at hour t.

System Constraints:

D_t	System load demand at hour t,
SR_t	System spinning reserve requirement at hour t,
OR_t	System operating reserve requirement at hour t.

Start up and shut down costs:

ST_i	Constant start up cost for unit i,
SD_i	Shut down cost for unit i,
CSU_{it}	Total start up cost for unit i at hour t,
CSD_{it}	Total shut down cost for unit i at hour t.

Cost functions:

C_{i0}	No load cost for unit i,
c_{it}	Operational cost of unit i at hour t (including no load cost),
IC_{im}	Incremental cost for unit i at cost segment m,
MW_{im}	Maximum power value for unit i at cost segment m.

Capacity constraints:

$PMIN_i$	Minimum capacity for unit i,
$PMAX_i$	Maximum capacity for unit i.

Reserve constraints:

MSR_i	Maximum sustained rate for unit i (MW/min),
QSC_i	Quick start capability for unit i.

Minimum up and down time constraints:

MU_i	Minimum up time for unit i,
MD_i	Minimum down time for unit i.

Initial conditions:

TD_{i0}	Number of hours that unit i has been offline initially,
TU_{i0}	Number of hours that unit i has been online initially,
U_{i0}	Initial commitment status of unit i (binary, 1 if it is online),
P_{i0}	Initial generation amount (MW) for unit i.

Ramping constraints:

RU_i	Ramp up rate for unit i,
RD_i	Ramp down rate for unit i.

Variable start up cost constraints:

ST_{im}	Variable start up cost for unit i being started up at cost segment m,

TD_{im} Shut down time (the maximum number of hours that the unit i being shut down at start up cost segment m).

The Objective Function of the SCUC Algorithm

Piecewise convex cost function is given as follows:
($C_{i0}u_{it}$ refers to the no-load cost.)

$$c_{it} = C_{i0}u_{it} + \sum_m IC_{im}px_{it,m}, \quad \text{(A.1a)}$$

$$p_{it} = \sum_m px_{it,m}, \quad \text{(A.1b)}$$

$$0 \leq px_{it,m} \leq MW_{im}. \quad \text{(A.1c)}$$

The piecewise non-convex cost function is given as follows:

$$c_{it} = C_{i0}u_{it} + \sum_m IC_{im}px_{it,m}, \quad \text{(A.2a)}$$

$$p_{it} = \sum_m px_{it,m}, \quad \text{(A.2b)}$$

$$MW_{i1}\delta_{it,1} \leq px_{it,1} \leq MW_{i1}u_{it} \ , \ m=1 \ (the\ first\ piece,) \quad \text{(A.2c)}$$

$$MW_{im}\delta_{it,m} \leq px_{it,m} \leq MW_{im}\delta_{it,m-1}, \ \ 2 \leq m \leq M-1, \quad \text{(A.2d)}$$

$$0 \leq px_{it,m} \leq MW_{im}\delta_{it,m-1}, \ \ m = M \ (the\ last\ piece). \quad \text{(A.2e)}$$

The objective function of the SCUC algorithm is given below:

$$\sum_i c_{it} + \sum_i CSU_{it} + \sum_i CSD_{it}. \quad \text{(A.3)}$$

The list of constraints considered are given as follows:

- Operational costs of generators, {A.1a-A.2e}
- Variable start-up and shut-down costs of generators, {A.6-A.8h}
- Capacity limits of generators, {A.9}
- Operating and spinning reserve requirements of the network, {A.10-A.12}
- Ramp up and down constraints of generators, {A.13-A.14}
- Minimum up and down time constraints of generators, {A.15a-A.16d}
- Load balance and reserve requirements, {A.17-A.19}
- Transmission Line and DC Load Flow Constraints {A.20-A.23}

Start Up and Shut Down Indicators of Generators

The start up and shut down indicators are given as follows:

$$y_{it} - z_{it} = u_{it} - u_{i,t-1}, \tag{A.4}$$

$$y_{it} + z_{it} \leq 1. \tag{A.5}$$

Start Up and Shut Down Cost Constraints of Generators

$$CSU_{it} = ST_i y_{it}, \tag{A.6}$$

$$CSD_{it} = SD_i z_{it}. \tag{A.7}$$

Variable Start Up Cost Constraints of Generators

Formulization is given on an example start up curve as given in Figure A.1.

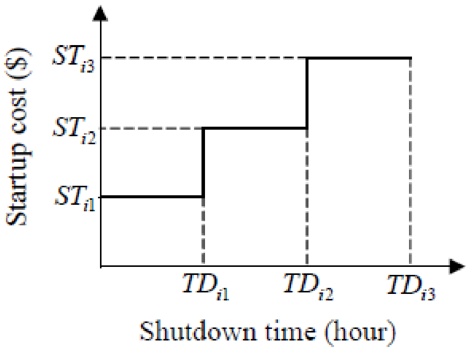

Figure A.1 Start up Cost Curve for Unit i (i_{th} Generator).

The formulation is as follows:

$$0 \leq sd_{it} \leq MF_i(1 - u_{it}), \tag{A.8a}$$

$$1 - (MF_i + 1)u_{it} \leq sd_{it} - sd_{i,t-1} \leq 1, \tag{A.8b}$$

$$sd_{it} = \sum_m v_{it,m}\left(TD_{i,m-1} + 1\right) + zv_{it}, \tag{A.8c}$$

$$cst0_{it} = \sum_m v_{it,m}\, ST_{im}, \tag{A.8d}$$

$$\sum_m v_{it,m} = 1 - u_{it}, \tag{A.8e}$$

$$0 \leq zv_{it} \leq \sum_m\left(TD_{im} - TD_{i,m-1} - 1\right)v_{it,m}, \tag{A.8f}$$

$$0 \leq cst_{i,t+1} \leq MST_i y_{i,t+1}, \tag{A.8g}$$

$$0 \leq cst0_{it} - cst_{i,t+1} \leq MST_i\left(1 - y_{i,t+1}\right). \tag{A.8h}$$

MF_i is the maximum hours a unit could be OFF, sd_{it} is the current shut down time, $cst0_{it}$ is the start up cost for unit i at hour t, MST_i is the unit i's maximum start up cost, v is the number of hours that the unit is OFF in segment m, and m is the number of cost segment in units' start up cost curve.

Capacity Constraints of Generators

$$PMIN_i u_{it} \leq p_{it} \leq PMAX_i u_{it,} \tag{A.9}$$

Reserve Constraints of Generators

$$p_{it} + sr_{it} \leq PMAX_i, \tag{A.10}$$

$$0 \leq sr_{it} \leq u_{it}\,(10MSR_i), \tag{A.11}$$

$$or_{it} = sr_{it} + (1 - u_{it})QSC_i. \tag{A.12}$$

Ramping Constraints of Generators

$$p_{it} - p_{i,t-1} \leq y_{it}PMIN_i + (1 - y_{it})RU_i, \tag{A.13}$$

$$p_{i,t-1} - p_{it} \leq z_{it}PMIN_i + (1 - z_{it})RD_i. \tag{A.14}$$

Minimum Up and Down Time Constraints of Generators

The formulation used for minimum up time constraint is given below:

$$UT_i = max\{0, min[NH, (MU_i - TU_{i0})U_{i0}]\}, \tag{A.15a}$$

$$\sum_{t=1}^{UTi}(1 - u_{it}) = 0, \tag{A.15b}$$

$$\sum_{m=t}^{t+MUi-1}(u_{im}) \geq MU_i y_{it}, \qquad \forall t = UT_i + 1, \dots, NH - MU_i + 1, \tag{A.15c}$$

$$\sum_{m=t}^{NT}(u_{im} - y_{it}) \geq 0, \qquad \forall t = NH - MU_i + 2, \dots, NH. \tag{A.15d}$$

The formulation used for minimum down time constraint is given below.

$$DT_i = max\{0, min[NH, (MD_i - TD_{i0})(1 - U_{i0}]\},$$ (A.16a)

$$\sum_{t=1}^{DTi} u_{it} = 0,$$ (A.16b)

$$\sum_{m=t}^{t+MD_i-1} (1 - u_{im}) \geq MD_i z_{it}, \quad \forall t = DT_i + 1, \dots, NH - MD_i + 1,$$ (A.16c)

$$\sum_{m=t}^{NT} (1 - u_{im} - z_{it}) \geq 0, \quad \forall t = NH - MD_i + 2, \dots, NH.$$ (A.16d)

System Load Balance and Reserve Requirement Constraints

$$\sum_i (p_{it}) = D_t,$$ (A.17)

$$\sum_i (sr_{it}) \geq SR_t,$$ (A.18)

$$\sum_i (or_{it}) \geq OR_t.$$ (A.19)

Transmission Line and DC Load Flow Constraints

The DC power flow equations are modeled as follows:

$$B'\theta + B_\Delta \Delta = PG - PD, \quad i \in \{1, \dots \dots NB - 1\}, \quad m \in \{2, \dots \dots NB\},$$ (A.20)

$$PL_{im} = \frac{(\theta_i - \theta_m - \gamma_{im})}{x_{im}},$$ (A.21)

$$PL_{im}^{min} \leq PL_{im} \leq PL_{im}^{max},$$ (A.22)

$$\gamma_{im}^{min} \leq \gamma_{im} \leq \gamma_{im}^{max}.$$ (A.23)

B' is the admittance matrix, θ is the bus voltage angle vector, B_Δ is the phase shifter incidence matrix, and Δ is the phase shifter angle vector. PG is the generation vector, and PD is the demand vector. γ_{im} is the angle of phase shifters, x_{im} is the per unit reactance of lines, and PL_{im} is the amount of power flow on the lines between bus numbers i and m.