Az SMART
Arizona's Solar Market Analysis and Research Tool

Modeling and Management of Distributed PV Generation and Storage Units

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Systems and Industrial Engineering
THE UNIVERSITY OF ARIZONA®

December 2011

Executive Summary

The significance of renewable energy in the current energy system has been increasing. The concerns in greenhouse gas emission motivate researchers to improve technology for distributed energy resources (DG) and this result in price drop of DG generated electricity. In addition, federal government and state legislatures forces utility companies to generate energy more from alternative energy sources and also motivates customers with incentives. These encouragements have high impact in energy market.

Photovoltaic system (PV) becomes much more financially attractive among DGs since its payback period is significantly lower. Many solar energy installation companies offer various services for residential customers to get most benefit out of PV generations. However, installing large amount of PV panels for companies, universities, and government institutions is more challenging than residential customer installations, specifically selection of location and size of panels requires additional attention. Moreover, installing energy storage as an additional energy sources in the case of black out and PV intermittency is more challenging since the price of storage per kWh is currently higher than PV generated price. Detailed study and decent planning are needs to be offered since it requires significant financial investments in the long term.

The main objective of this research is presenting a framework that offers a complete study to determine the best locations and capacities for solar panels with storage units for campus type environment considering profit maximization, electricity stability, and emission factors. Framework integrates and utilizes various efficient methods to present complete tool for medium and large scale investors.

GIS module presents an analysis tool that calculates the available roof tops for buildings in specified area. LIDAR (Light Detection and Ranging) data is processed by user defined filters in ArcGIS software. *Mathematical programing-based optimization module* offers a detailed model that considers maximizing the PV installation profits for user defined number of years. Current and estimated future electricity price, installation and maintenance prices for PV panels and inverters, incentives, and various constrains are formulated to present installation plan in certain years. *Simulation module* presents a technical approach to satisfy the PV installations that are

planned in previous optimization module. Power distribution network of the selected area is modeled in PowerWorld® simulation program for power flow analysis. Each year PV installations are verified and finalized with the simulations for voltage profile limits.

If there is a voltage limit violations in the simulations due to the PV installation, framework proposes two solutions. *Re-allocation module* proposes a new calculation method for new location and size for PV installation that exceeds the voltage limits. *Storage Module* proposes another solution by installing storage unit next to the PV system. Charging and discharging of storage not only provides additional energy sources but also help to keep the voltage within the limits of ±5%. Since installing storage units as is an addition into the system, new installation plan for profit maximization is proposed to decide when to install the storage unit by considering electricity price, storage installation and maintenance prices.

University of Arizona (UA) campus is considered as a case study. LIDAR data for four square mile campus area is processed with GIS module and the available rooftops in the campus buildings are calculated. PV installation plan for twenty year is optimized with maximum profit by optimization module. Simulation module develops an on-line diagram of campus distribution network and run for power flow results with the PV installations. Re-allocation and storage modules are run according to the simulation results. Results show that this framework proposes both economic and technical benefits by considering different aspects in one program.

Although this framework focuses on UA campus PV installations only, it can be applicable to many other campus type environments. The framework either can be a single tool or each module can be used as a separate tool depends on the need. This framework has the potential to be an appropriate tool for various applications. Potential area of applications and customers with their interests are summarized in two different groups in the tables below as 1) centralized management of campus type environment and 2) centralized management of single buildings located in different places. Table also shows which module can be used for the customer needs.

Group 1: Centralized management of campus type environment

Customers	Interests	Related module (GIS,OM, SIM, STM and Complete Module: CM)	Potential to be a customer
Government Buildings			
Military	• Security • Meet demand	CM	High likely
Municipalities (parks, fairgrounds etc.)	• Meet demand • Reduce emission • Outreach	GIS and OM	Likely
Government agencies (e.g. police stations)		CM	High likely
Research Institutions			
Corporate campus (Research and Manufacturing Companies, e.g. Intel)	• Research • Meet demand • Get incentive from federal • Increase reliability • Reduce the cost	CM	High Likely
Hospitals	• Provide uninterruptable service to patients.	SIM	Likely
Home Development and Management Companies			
Retirement communities	• Meet demand • Reduce the cost • Get incentives	GIS and SIM	Likely
Apartment complex			Likely
Shopping malls (e.g. Arizona Mills, Tucson Mall)			High likely
Educational Institutions			
High/Elementary Schools	• Educational • Meet demand • Reduce emission • Outreach	CM	High Likely
Community Collages			
Universities			
Others			
Airports	• Increase reliability	CM	Low to medium
Agricultural companies	• Reduce the cost	CM	Likely
Religious institutions (e.g. Church)	• Education • Meet demand	GIS and SIM	Likely
Banks	• Security	GIS and SIM	Likely

Group 2: Centralized management of single buildings located in different places:

Customers	Interests	Related module (GIS,OM, SIM, STM and Complete Module: CM)
Department Stores		
Wal-Mart	• Meet demand • Get incentives • Outreach	CM
Target		
BestBuy		
Macy's		
Office max		
Office depot		
Ross		
Home depot		
Kohl's		
Fast Food and Restaurant Chains		
McDonalds	• Meet demand • Get incentives • Outreach	CM
Burger King		
Subway		
Starbucks		
Olive Garden		
Cheese cake factory		
Agencies and Organization Chains		
UPS, FedEx	• Meet demand • Get incentives • Outreach	CM
Airline agencies		
Insurance agencies		
Factories		
GM	• Reduce emission • Reduce the cost • Outreach	CM
Ford		
Small Residential and Commercials		
Individual houses	• Meet demand • Get incentives • Reduce the cost	SIM
Small businesses		

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Nomenclature

ACC	Arizona Corporation Commission
AGC	Automatic generation control
AVR	Automatic voltage regulator
DEM	Digital elevation model
DG	Distributed generation
GAMS	General Algebraic Modeling System
GIS	Geographical Information System
kWh	Kilowatt hour
LIDAR	Light Detection and Ranging
NREL	National Renewable Energy Laboratory
p.u.	per unit
PV	Photovoltaic
PW	PowerWorld®
RECPP	Renewable Energy Credit Purchase Program
TEP	Tucson Electric Power
UA	University of Arizona

1. Introduction

There has been a growing interest in renewable energy resources particularly for grid connected distributed electricity generation (DG). Solar Photovoltaic (PV) systems have received the most attention due to their environmental friendly power generations, technological advances in panel efficiencies and easy installations, and financial incentive programs. However, being geographically distributed, the intermittent and sudden change of weather as well as high price makes the PV installations more challenging (Freris and Infield 2008). Accurate sizing of PV installations and their locations that can economically and technically satisfy the demand is one of the ongoing research questions. In addition, energy storage system would bring further problems when storage is considered to reduce the variance of PV generation and provide additional energy source. The energy storage device prices do not decrease fast enough as the PV price does, hence, planning and defining storage size and installations have vital importance.

This research proposes a framework that presents a complete study to determine the best locations and capacities for solar panels with storage units for UA campus area and Tucson considering profit, electricity stability, and emission factors via integration of

- GIS Analysis
- Mathematical programming-based optimization
- Simulation.

PV installations for UA campus for twenty years are studied both economically and technically. The framework develops a long-term PV installation strategy in two levels. Macro level concerns the available roof tops of the campus buildings and maximizes twenty year profit of PV installations for the campus. Micro level focuses on electrical distribution system simulations of UA campus with the additions of PV installations to explore the impact of installations into the current infrastructure in the case of PV additions. The program uses data that are provided by UA Facility Management, Tucson Electric Power (TEP), Pima Associations of Governments, UA Physics Department and Google Maps.

This study has the contribution of combining many aspects for long-term PV installation in one program. This framework proposes a unique approach that contains different aspects (optimization, economic and technical parts, simulations) in one tool and runs various methods at one time for long-term installations. UA campus area is considered as a case study; however, this tool is applicable to any given area such as bigger Tucson area. Framework includes different modules which can work as a complete tool as well as separate tools depend on the need. The rest of the paper is organized as follows. Section 2 reviews the related work and background of the DG and its application. Section 3 presents the framework of the proposed tool. Section 4 through Section 8 explains the details of each modules used in the framework. Section 9 concludes the paper.

2. Background and Literature Review

There are various research studies conducted on renewable energy applications, specifically solar energy field and their integrations with the utility grids. Both technical and economic impacts of the PV systems are investigated. The size and location of the PV installations are other topics of some studies such as (Fidalgo, Fontes and Silva 2009). The various locations and sizes of distributed generations are simulated and the impacts of penetration level and location are investigated. Power flow study results of voltage profile and system losses of the distribution network are the criteria showing the impacts of PV generations. Power flow simulations are calculated mathematically other than using a software package. Large scale PV installations are studied by (Muneer, Bhattacharya and Cañizares 2011).An optimum location and size for 30 year investment plan is presented. However, not a detail simulation study is performed. Another optimum placement of PVs is studied by (Hejazi, et al. 2010). Multi-objective optimization that minimizes the energy coast is presented. Voltage profile of a distribution test case is investigated for various cases using the objective functions. However, again a detailed simulation study and a long-term planning are not is presented in this work too. Optimum sizing of PV and battery via simulation calculations are focused in (Muselli, et al. 2000). The work by (Kaabeche, Belhmael and Ibtiouen 2011) combines the optimum sizing of hybrid energy systems both technically and economically, however, not for long-term installations. Solar radiation fluctuation is studied by (Kaplani and Kaplanis 2011) and the optimum PV and battery sizing is calculated through stochastic simulations. A multi-objective planning framework is presented by (Alarcon-Rodriguez, et al. 2009) for integration of stochastic and controllable distributed energy resources. A distribution network case study is used as a case study but not a complete simulation study is presented. A detailed study on PV installations for Pennsylvania State University is presented as a class project by a group of students (Ositelu, et al. 2010). The work includes the calculations of available roof tops in the campus through satellite pictures. Simulation studies are presented; however, it is not a detailed online simulation and not investigates the voltage profile. Economical aspect of the PV installations for the university is studied but not for long-term planning.

Some studies investigated the impact of PV installations in to the existing distribution network. A report by (Agent 2009) focused on the voltage profile of the system after the PV additions and proposes batteries as a supplement to fix the over and under voltage problems. This study is used a reference at battery module along with (Nishikawa and Kazuhiko 2003) which also presents a work on the battery usage that helps the bad voltage profile due to the PV installations. Detail research is presented on battery characteristics and their types, the role, and effects on the system by National renewable Energy Laboratory in (Eyer and Corey 2010).

Considering all the above studies, the proposed framework presents research in broad area that brings many studies together for long-term installations of PV installations for campus type environment. Economic studies are presented through mathematical programing-based optimization algorithms and technical studies are presented through simulations that check the applicability of the PV installations.

3. Framework Description

The proposed framework consists of two main levels and five modules. Macro level includes GIS and Optimization modules, Micro level includes Simulation module. Re-allocation and Storage modules are both in macro and micro levels. Figure 1 shows the framework program flow chart. Program starts with the processing of LIDAR (Light Detection and Ranging) data[1] that includes the four square mile of UA area. The filters defined in GIS module (ArcGIS software) process the LIDAR data and generate an output that lists the number of PV panels that can be installed on available rooftops of university buildings. The available rooftops with number of PV panels are used in Optimization module to maximize the profit of PV installations in twenty years. Optimization module runs a mathematical programming-based optimization considering

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[1] Obtained from Pima Associations of Governments

the data[2] that includes the predicted PV panel costs, future incentives and future electricity price. The output of the module is the optimum location and size of PV panel installations in next twenty years. Each year installations are provided to the next Simulation module. This module uses PowerWorld® (PW) simulation program that calculates the power flow of given electric power distribution network.

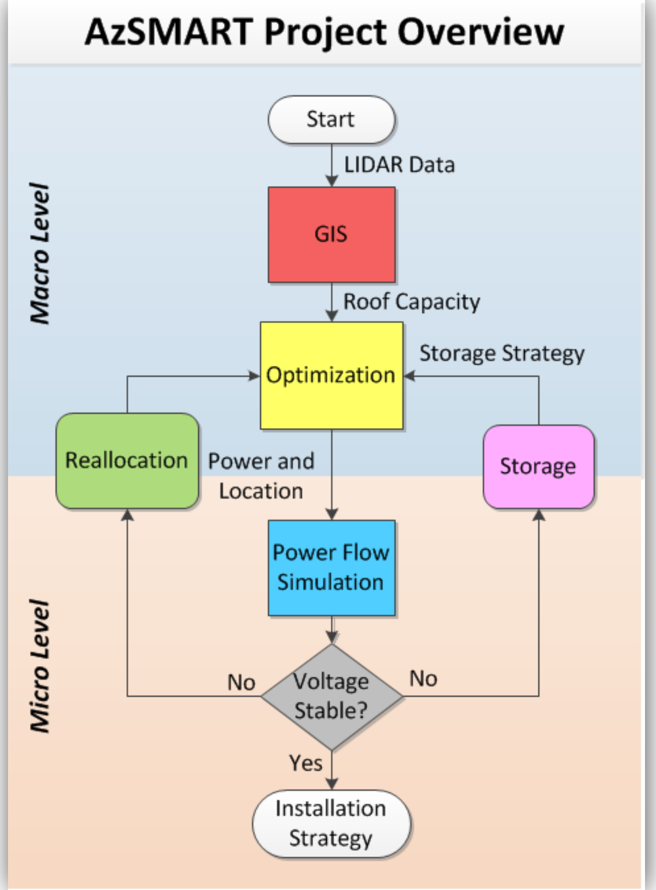

Figure 1 Framework program flow

In this framework, UA campus distribution network is modeled in PW and PV installations coming from the optimization module are added as power generations. Simulations are run with the added PV generations and the voltage profile of the network is checked. If the bus voltages are within the limits of ±5% of 1 p.u, the calculated PV installations are appropriate both economi-

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[2] Data is provided by TEP

cally and technically, and can be integrate with the existing campus power network. If the voltage is not within the limits, program offers two modules as a solution: Re-allocation and Storage modules. Since the amount and the location of PV are not appropriate, changing the location and the amount helps to correct the voltage profile. Re-allocation module calculates new location and amount of PV generation based on a rule. New PV location is tested and voltage profile is checked with power flow simulations. This process repeats unless the voltage profile is satisfied. Storage module presents another solution by adding a storage right next to the PV installations. Charging and discharging storage helps to keep the voltage profile within the limits and the amount of storage is defined by a rule of thumb through simulations. This solution has high coast comparing to the Re-allocation module solution, therefore, an installation plan for installing the storage is optimized for future years. This whole process repeats for each year installations until the voltage profile is within the limits. All the simulations are run for two cases; steady state and time-step simulations for sunny and cloudy days.

4. GIS Module

Geography Information System (GIS) is a system designed to capture, store, manipulate, analyze, manage, and present all types of geographically referenced data (ESRI 2009). In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology. GIS has advanced a lot during the past decades with the development of information technologies, data collecting and aeronautics. GIS has been used as an application in numerous fields, such as earth surface-based scientific investigations, resource management, location planning, and environment impact assessment. Dean Djokic implemented Dijkstra's Algorithm into GIS and determined several routines for water flow and transport (Djokic and Maidment 1993). Shawna used GIS to explore the distribution of invasive alien plants to do spatial regression analysis (Dark 2004). Stan presented GIS-based potential modeling in Dutch physical planning practice (Geertman and Ritsema Van Eck 1995). Voivontas developed a GIS decision support system to determine the distribution of the economically exploited biomass potential (Voivontas, Assimacopoulos and Koukios 2001).

Since the need for on renewable energy increases, many scholars focus on solar energy research. However, some new methods are needed since the traditional methods seem to be inefficient. As an integrated system, GIS provides database calculation, real data analysis and user-defined programming, which can help us simplify our work on solar energy. Combination of GIS module with solar energy research has got big attention in the last decades. Bent used a GIS to model solar resources based on satellite data and to match it with demand modeling on a habitat basis. Combined with land use data, PV potential use is presented on the basis of practical areas for collection use (Sorensen 2001). GIS implemented to renewable energy applications in many aspects. Solar radiance, wind speed, grid distance and house density are recalculated and selected by GIS to determine how much power of each type (Amador and Dominguez 2005). Adel and Yassine generated solar radiation maps using GIS and showed the area that is high potential of solar radiation. At last, they did some sensitivity analysis on slope using GIS (Gastli and Charabi 2010).Marcel etc. al used GIS to calculate the expected average annual electricity generation of a standard PV system and the theoretical potential of PV electricity generation (Suri, et al. 2007).

In this study, GIS is expected to find the suitable roof tops for PV panel installations and determine the maximum number that can be installed for certain PV panels at certain buildings. This study is presented earlier (Chaves and Bahill 2010) with its details and briefly re-described in this section. Five filters are built in GIS module to find the suitable location of PV panels' installation by considering height, slope, aspect, radiance and human factors. Maximum number of PV panels at each location is calculated based on some assumptions and algorithms defined in ArcGIS.

4.1. Data pre-processing

The original input of GIS module is LIDAR (Light Detection And Ranging) data obtained from Pima Associations of Governments. LIDAR data contains numerous useful information including sun irradiance, slopes, aspects, heights and areas of certain place. LIDAR uses ultraviolet, visible, or near infrared light to image objects and can be used with a wide range of targets, including non-metallic objects, rocks, rain, chemical compounds, aerosols, clouds and even single molecules (Cracknell and Hayes 2007). Owing to its comprehensive information, LIDAR has been used widely for academic research as well as commercial uses.

LIDAR data is a raw data and cannot be used directly before pre-processed since all the information is combined together. “Fusion” software from Forest Service is used to export LIDAR data as a digital elevation model (DEM), which can be used in ArcGIS software. The digital elevation model obtained from “Fusion” is shown in Figure 2. The model analyzed four square miles surrounding the University of Arizona in Tucson.

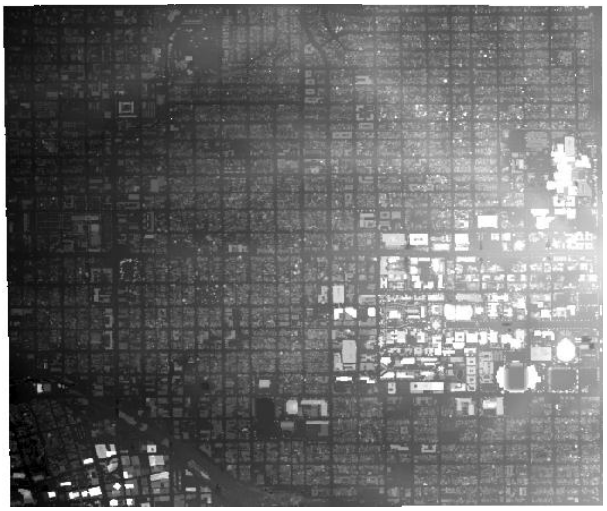

Figure 2 Digital elevation model from fusion

However, since the DEM is not geo-referenced, the data is needed to be geo-referenced using the Georeferencing Toolbar in ArcGIS, which can be used to build GIS model. Before modeling, verification of geo-referenced DEM layer is needed. The resulting dimensions and point locations of the geo-referenced image is verified with the use of several points whose location is known with certainty.

4.2. Modeling in GIS

Some solar radiation information correspond to latitude is included within the ArcGIS software. A solar map is generated from the geo-referenced image specifying Tucson’s latitude of 32 degrees and a yearly interval. This solar map considers several factors which would influence the radiance, such as the changes in the elevation, the position of the sun as well as any shading effect caused by buildings or other objects in the input raster. If the result of solar map is higher than the pre-defined threshold, there exists sufficient radiance to install PV panels and assign the value of cell to 1. The result of the solar map is shown in Figure 3. The green part in the figure is the suitable part for installation considering radiance.

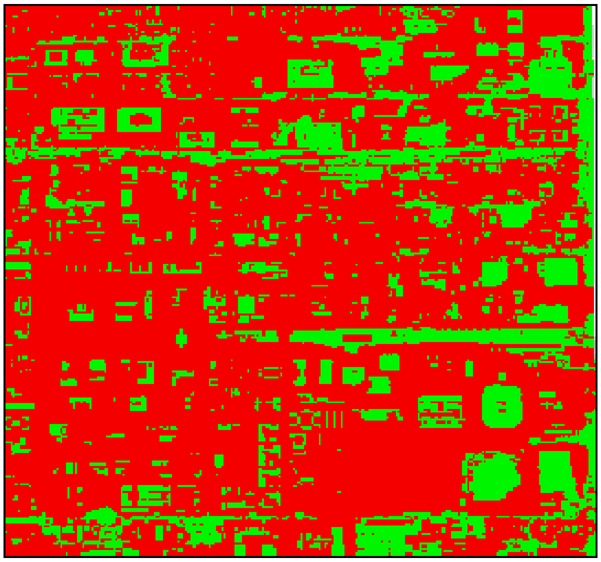

Figure 3 Radiance filter

Besides the solar map layer generated earlier, other factors should also be considered. Intuitively, solar panels should be installed on the top of certain buildings in the campus. Therefore, an elevation layer is needed to get rid of the ground part of campus. A bare-earth file is generated from the DEM and geo-referenced to the same coordinates as the input image. Then a binary ground raster is generated that assigned a value of 1 for any non-ground cell higher than or equal to five feet and assigned 0 to all others, which are ground cells. The result of elevation layer is shown in Figure 4. The green part in the figure is the suitable part for installation considering elevation.

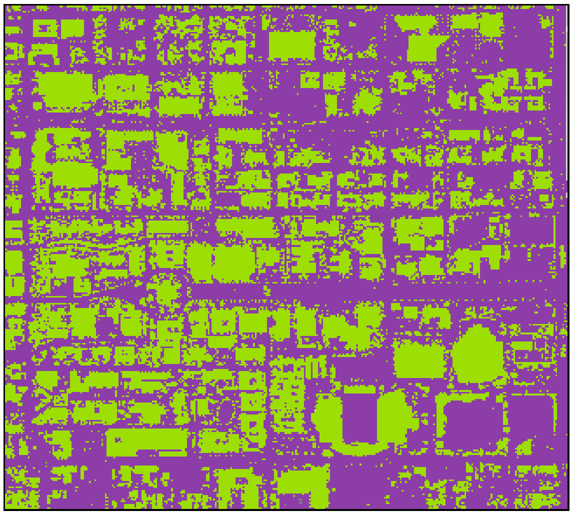

Figure 4 Elevation filter

The aspect of location for installation should be south facing or horizontal since Tucson is located in the northern hemisphere, solar panels located on south-facing slopes will have a higher solar power output than those located on north-facing slopes. An aspect raster is generated from the geo-referenced image. The cells that have south, southeast, southwest or flat aspects are assigned the value of 1; others are assigned the value of 0. The result of aspect layer is shown in Figure 5. The blue part in the figure is the suitable part for installation considering aspect.

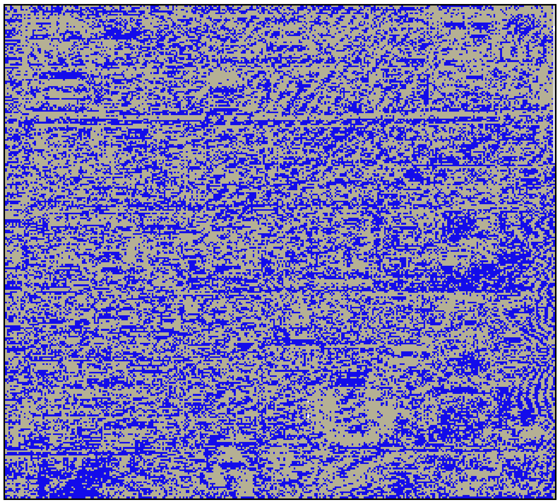

Figure 5 Aspect filter

Moreover, the slope of the roof should be less than 35 degrees, which means the PV panels can face the sunshine perpendicularly. The result of slope layer is shown in Figure 6. The purple part in the figure is the suitable part for installation considering slope.

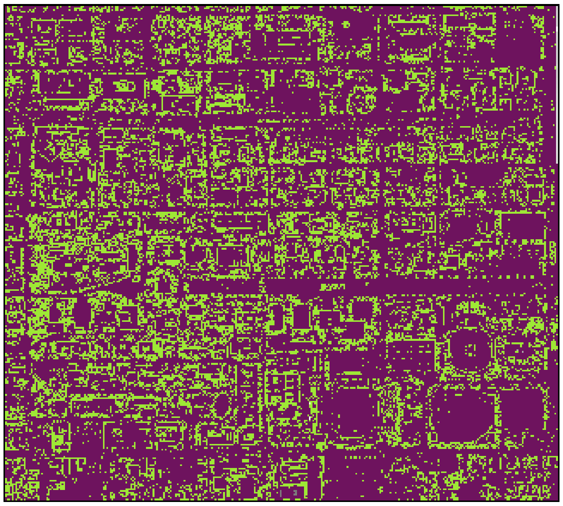

Figure 6 Slope filter

In addition, other information which cannot be acquired from GIS and LIDAR data should be considered as well, such as roofs with pipes, air conditioning units, athletic stadium seats and so on. According to the five filters defined earlier, all of them are combined into a final raster. If the value of any cell in the final raster is equal to 1, it means that the cell is a suitable place to install PV panels. The final result is shown in Figure 7. The green part is the suitable place for installation considering all the factors described above.

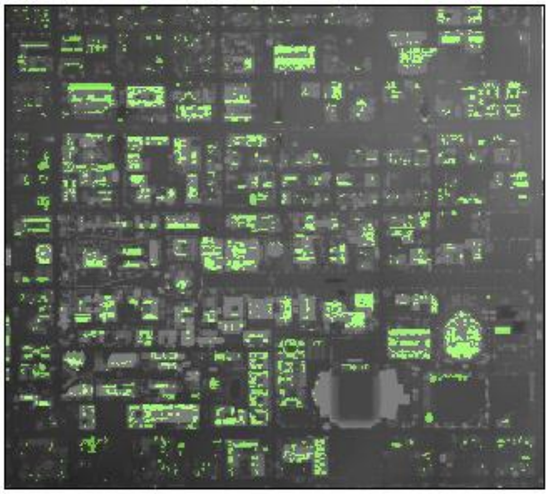

Figure 7 Suitable place of PV installation

4.3. Result analysis

In order to calculate the available area for PV installations, it is assumed that each PV panel has one and a half square meter surface area which is an average number for PV panels in the market. Since area calculation of rooftops in GIS is provided, the maximum number of PV panels on each building is calculated. The result can be shown in Figure 8 and Table 1.

Table 1 Percentage of suitable buildings for different installation strategies

# of Solar Panels	Theoretical Max	1	5	10	25	50	100
Area	460429.4	459844.6	444162.7	418968.9	347408.5	260259.1	180693.0
Area as % of buildings	4.70%	4.70%	4.54%	4.28%	3.55%	2.66%	1.85%
# of solar panels	306953	301050	292220	276391	230150	172866	120194
Total Capacity (MW)	45.6	44.7	43.4	41.0	34.2	25.7	17.8

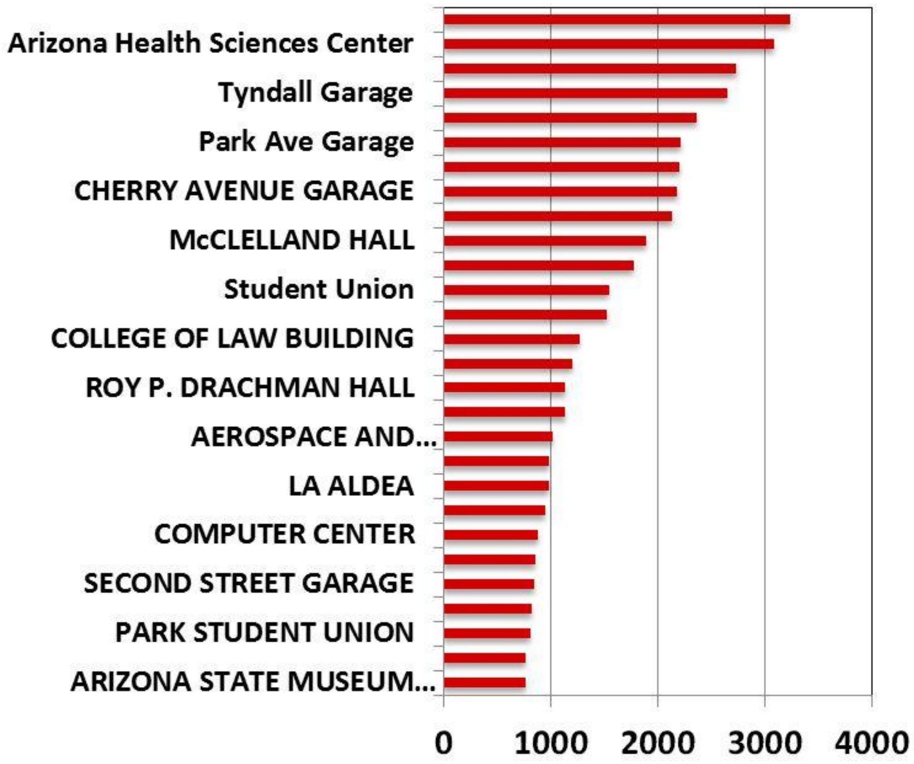

Figure 8 Capacity of each building

5. Optimization Module

One of the main concerns in the design of a long term distributed generation (DG) system is the accurate selection of annual DG system size and its location that can economically satisfy the demand. This depends on the suitable and available spaces for solar panels, the capital and running cost of system components, and the annual load that ought to be met. In this module, a formulation for optimizing the design of twenty year PV installation is developed. This formulation employs integer programming techniques to maximize twenty year profit of installing PV panels. The developed computer programming receives the necessary input data (e.g. available roof tops, installation and maintenance coast, incentive rates, etc.), and computes the number of the panels that should be installed in different roof tops. The program also decides about the type of panel that should be installed. In order to study the effect of parameters predefined, several sensitivity analysis studies are performed, and the effect of federal and state tax credits, utility rate, load growth, maximum available suitable solar area, and inverter life time are investigated. According to the result of GIS module and target set by TEP and UA, capacity constraint, lower bound generation target constraint and emission constraint are added. Since with the installation of PV panels, power stability, especially voltage instability, becomes more and more significant, another stability constraint which forces the installation to be distributed more uniformly to enhance the stability of whole PV system is used. The proposed optimization technique is tested on University of Arizona data as a part of framework.

Index/Set

m	set of locations to install PV panels
k	set of PV panel types
t , f	set of period to install PV panels

Parameters

ASH	Annual sunny hours in Tucson
dr	derating factor
$UR(f)$	Utility rate in year f
r	Discount factor
$\mathrm{e}(\mathrm{k}, \mathrm{y})$	Power output of panel type k with age y
$H(\tau)$	Monthly average of daily solar insolation in month τ
$P(k)$	Failure rate of inverter with age k
$D(\tau)$	Number of the days in month τ
α	Maintenance coefficient as percentage of installation cost
$L(t)$	Minimum amount of energy generation in year t
$Ca(m)$	Roof capacity of building m
$NSC(t,k)$	Net system cost of PV installation in year t for panel type k
$C(t)$	Inverter replacement cost in year t
$AE(k)$	Avoided emission of pollutant type k
$AET(k)$	Target of emission reduction for pollutant type k
$M(t)$	Upper bound for total installation in feeders in year t
$m(t)$	Lower bound for total installation in feeders in year t

DecisionVariables

TB	Total benefit
$IC(t)$	Installation cost in year t
RC	Total inverter replacement cost
OMC	Operation and maintenance costs
$n(t,k,m)$	Number of panel type k installed in year t on building m
IC	Total installation cost
$X(t)$	Total number of inverters installed in year t
$I(t)$	Number of Inverters installed in year t for newly installed panels
$V(t,s)$	Amount of power generated on buildings of feeder s in year t

5.1. Formulating the problem

The goal of the optimization technique is to determine annual size, type and location of PV panels so that the constraints can be economically satisfied. For this reason, the decision variables are number, location and type of the panels which must be installed in each year. The objective function to be maximized is total profit of installing PVs in T years and the constraints are expressed through load requirement, roof capacity, emission factor, uniform distribution of PV panels among sub-grids. The distribution network of whole campus is divided into four parts, which is called as sub-grids, to investigate the voltage profile and its stability. The objective of this model is maximize the total profit, hence, the objective function is generated by summation of the present value of total benefit of PV installation (TB), total installation cost (IC), total inverter replacement cost (IRC) and operation and maintenance cost (OMC). The profit function can be written as:

$$max\{TB - IC - IRC - OMC\} \tag{1}$$

Following sections explains each components of the objective function.

5.1.1 Total benefit (TB)

One of the major benefits offered by DG is the avoided cost that the costumer saves for not buying the electricity from utility. The total benefit in time horizon of the project (F) will be summation of present value of benefit of each year. Given $UR(f)$, the utility price per kWh in year *f*, the present value of utility rate is equal to $UR(f)/(1+r)^f$. Total benefit is given by

$$TB = ASH \times dr \times \sum_{f=0}^{F} \frac{UR(f)}{(1+r)^f} \sum_{t=0}^{f} \sum_{k=1}^{K} \sum_{m=1}^{M} n(t,k,m)e(k,t) \tag{2}$$

where

$$ASH = \sum_{\tau=1}^{12} H(\tau) \cdot Day(\tau) \tag{3}$$

It should be noted that degradation of the PV panels weakens the systems output over time. Therefore, power output of panel type k is a function of its age . A derating factor dr is considered due to the loss of wiring, inverter and connectors. On the other hand, PV panels cannot generate all the time during the day, hence, Annual sunny hours in Tucson (ASH) is introduced in model to describe the generation of PV panels.

5.1.2 Total installation cost (IC)

There are several factors which would affect the cost of PV panel installations, such as labor cost, inventory cost and transportation cost. However, to simplify the problem, one assumption is predefined in the model as the cost of PV panels is linear with power generated. Considering different policy such as the tax credit, incentives and technology innovation, denote the cost of PV panels as Net System Cost (*NSC*). The total initial investment is calculated using an installation cost of $NSC(t,k)$ per kW as followings:

$$IC = \sum_{t=0}^{T} \sum_{k=1}^{K} \frac{NSC(t,k)}{(1+r)^t} \sum_{m=1}^{M} n(t,k,m)e(k,t) \tag{4}$$

In order to get the present value of installation cost in year *t*, discount factor *r* is considered.

5.1.3 Inverter replacement cost obtained by recursive relations

The lifetime of an inverter is usually shorter than that of a solar panel. Therefore, it might be necessary to purchase additional inverters before the life span of the project comes to the end. If the price of buying an inverter at year *t* would be $C(t)$ per kW, the present price can be calculated considering discount factor *r*. Inverters are bought once at the beginning of the each year for newly installed panels $I(t)$. The number of the inverters purchased for new panels is proportional to the amount of power installed, ρ. $X(t)$, the total number of inverters installed in year *t* is summation of inverters for replacement and inverters of newly installed panels, $I(t)$. As mentioned before, $P(t)$ is the failure rate of inverters with age *t*. Therefore, at year *t*, the number of failed inverters with age *t* would be *P*(*t*) times number of inverters with age *t*, *X*(*0*). Similarly, the number of failed inverter with its age at year *t* can be obtained. Therefore, the summation would be the total number of failed inverters at year *t*.

$$RC = \frac{1}{\rho}\sum_{t=0}^{T}\frac{C(t)[X(t)-I(t)]}{(1+r)^{t}} \tag{5}$$

with

$$X(t) = P(t)X(0) + P(t-1)X(1) + \cdots + P(1)X(t-1) + I(t) \tag{6}$$

$$I(t) = \rho\sum_{k=1}^{K}\sum_{m=1}^{M} n(t,k,m)e(k,t) \tag{7}$$

It should be noticed that installation cost for inverters of newly installed panels is considered in installation cost of PV panels in section 5.1.2. Therefore, *I(t)* should be subtracted in replacement cost of inverters.

5.1.4 Operation and maintenance costs

This cost includes issues periodical maintenance of PV panels such as regular dusting or washing of PV panels and inspection of electrical connections and inverters. It is assumed that the operation and maintenance cost in year *t* is proportional to total cost of installation in year *t*.

$$OMC = \alpha\sum_{t=0}^{T}\sum_{f=0}^{t} IC(f) \tag{8}$$

5.1.5 Constraints

The first constraint that ought to be met, while maximizing the objective function, is serving the annual renewable target. The annual target is used as a percentage of demand in these calculations. The second constraint that ought to be met is the available area which is suitable for PV installation. Therefore, the total number of PV panels installed in certain building cannot exceed its capacity. This data is provided by GIS module.

$$dr\sum_{k=1}^{K}\sum_{m=1}^{M} n(t,k,m)e(k,t) \geq L(t) \tag{9}$$

$$\sum_{k=1}^{K}\sum_{t=0}^{T} n(t,k,m) \leq Ca(m) \tag{10}$$

Another constraint to be considered is the target for environmental impact reduction. Introduction of DG will result in reduction of capacity needs of conventional plants due to two reasons: (1) the real power generated by solar panels will directly reduce the power needed from utility company and (2) the resulting line-loss reductions will further decrease the output needs from conventional plants (Chiradeja and R.Ramakumar 2004). Since Carbon Dioxide is the most emission during generation, only $\mathrm{CO_2}$ is considered in our model. If avoided emission of pollutant type *j*, $\mathrm{AE(j)}$ is given per *kW*, total *lbs* target of emission reduction for each type of pollutant should be more than the minimum target. This constraint can be written as

$$AET(j) \le AE(j) \cdot dr \cdot \sum_{t=0}^{T} \sum_{f=0}^{t} \sum_{k=1}^{K} \sum_{m=1}^{M} n(t,k,m) e(k,t) \tag{11}$$

Another constraint that should be taken into account is voltage stability. The location of DG has the main effect on system voltage stability. The effect of DG capacity and location on voltage of radial system shows that distributing the same capacity of DG at all feeders is better from voltage stability point of view than concentrating the same capacity at one or two feeders only (Hemdan and Kurrat 2008). Therefore, voltage stability should be considered as a constraint when dealing with optimum allocation of PV panels. $\mathrm{V(t,s)}$, amount of power generated on buildings of feeder *s*, in year *t*, can be calculated by

$$V(t,s) = dr \sum_{f=0}^{t} \sum_{k=1}^{K} \sum_{m \in S(s)} n(f,k,m) e(k,f) \tag{12}$$

The amount of power which is generated in year *t* at each feeder *s* should be among two predefined amounts.

$$m(t) \le V(t,s) \le M(t) \tag{13}$$

$$M(t) - m(t) \le w(t) D \tag{14}$$

According to the two formulas above, it can be forced that the difference of PV panel installation between each feeder is limited to some threshold to enhance the stability of the whole system.

After taking into account all the above items, the final model becomes as follows:

Objective Function:

$$
\begin{aligned}
\max z = {} & dr\sum_{\tau=1}^{12} H(\tau)\cdot Day(\tau)\sum_{f=0}^{F}\frac{UR(f)}{(1+r)^{f}}\sum_{t=0}^{f}\sum_{k=1}^{K}\sum_{m=1}^{M} n(t,k,m)e(k,t) \\
& -\sum_{t=0}^{T}\sum_{k=1}^{K}\frac{NSC(t,k)}{(1+r)^{t}}\sum_{m=1}^{M} n(t,k,m)e(k,t)-\frac{1}{\rho}\sum_{t=0}^{T}\frac{C(t)[X(t)-I(t)]}{(1+r)^{t}} \\
& -\alpha\sum_{t=0}^{T}\sum_{f=0}^{t}\sum_{k=1}^{K}\frac{NSC(f,k)}{(1+r)^{f}}\sum_{m=1}^{M} n(f,k,m)e(k,f)
\end{aligned}
\tag{15}
$$

Subject to:

$$
\begin{gathered}
X(t)=P(t)X(0)+P(t-1)X(1)+\cdots+P(1)X(t-1)+I(t) \\
I(t)=\rho\sum_{k=1}^{K}\sum_{m=1}^{M} n(t,k,m)e(k,t) \\
dr\sum_{k=1}^{K}\sum_{m=1}^{M} n(t,k,m)e(k,t)\ge L(t) \\
\sum_{k=1}^{K}\sum_{t=0}^{T} n(t,k,m)\le Ca(m) \\
AET(j)\le AE(j)\cdot dr\cdot\sum_{t=0}^{T}\sum_{f=0}^{t}\sum_{k=1}^{K}\sum_{m=1}^{M} n(t,k,m)e(k,t) \\
V(t,s)=dr\sum_{f=0}^{t}\sum_{k=1}^{K}\sum_{m\in S(s)} n(f,k,m)e(k,f) \\
m(t)\le V(t,s)\le M(t) \\
M(t)-m(t)\le w(t)D
\end{gathered}
\tag{16}
$$

5.2. Data used for calculations and optimization results

The developed optimization algorithm implemented in to UA campus as a case study. This section provides the data[3] used for calculations and the results of the proposed optimization. The time horizon for this test case is twenty years. Three types of panels have been considered in this study and their specifications are shown in Table 2. These panels are selected from the TEP test yard in which the performances of various PV panels are being investigated in Tucson weather condition.

---

[3] Data is provided by TEP

Table 2 Parameters of three types PV modules we used in our model

Manufacturer	Model	Technology	Approximate Surface Area	Pmppt (W)	Voc (V)	Isc (A)	Vmpp (V)	Impp (A)	Max System Voltage (V)
Sunpower	SPR-215-WHT-U	px-Si	1.25 m2	215	48.5	5.8	39.8	5.4	600
Kyocera	KC150G-A	px-Si	1.18 m2	150	28.50	7.26	22.50	6.67	600
Uni-Solar	PowerBond PVL	px-Si	0.93 m2	64	23.80	4.80	16.50	3.88	600

Solar radiance data was collected every month from 1961 to 1990 National Renewable Energy Laboratory (NREL) and the date for Tucson is used in this model. However, more data is available on the NREL website. Figure 9 (NREL 2007) shows the monthly average of daily solar insolation in Tucson. The data shown in the figure is monthly average number of thirty years from 1961 to 1990, which can be used to approximate the solar radiance in Tucson in the future since no significant changes occur. This data is used to calculate the annual sunny hour and power generation by PV panels in the model, which would make the result more accurate.

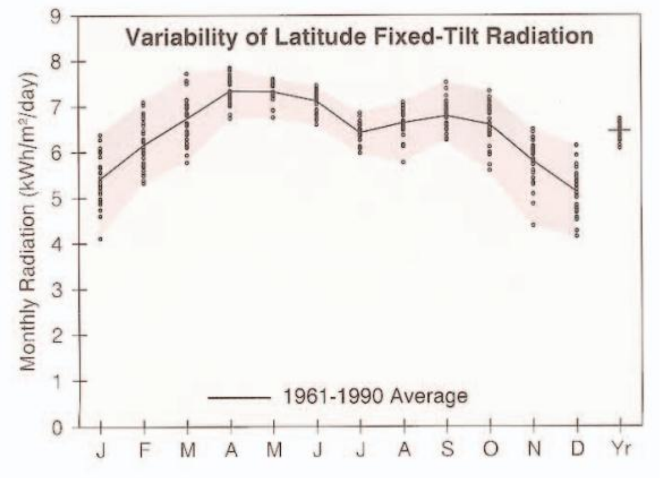

Figure 9 Yearly irradiance in Tucson

The utility rate changes every year according to the price of fuel, operation cost, policy and so on. The utility rate of Tucson increases every year as well as shown in Figure 10. This data is provided by TEP. The blue color in the following figure shows total base power supply charges, the red color shows fuel and purchase power charges and the black one shows environmental compliance.

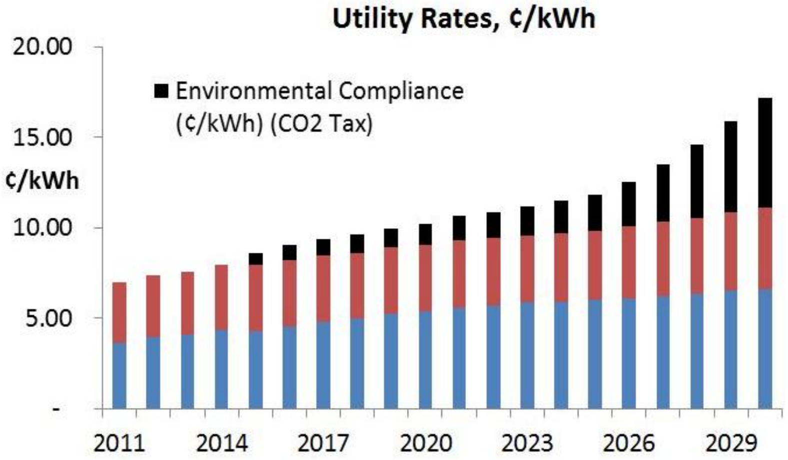

Figure 10 Utility rates in Tucson

It should be noted that photovoltaic power technology qualifies for federal and state tax credit and also Tucson Electric Power (TEP) Company is offering incentive payments through its Renewable Energy Credit Purchase Program (RECPP) for residential photovoltaic systems to encourage the installation of solar power. Even though the raw price of PV panels is very high, the net system cost of solar panels would be less owing to the benefits obtained from government and utility company. The Net System Cost of solar panels in Tucson is listed as follows. The Kyocera brand PV panel price is obtained and the prices of other panels are calculated intuitively according to the same formula.

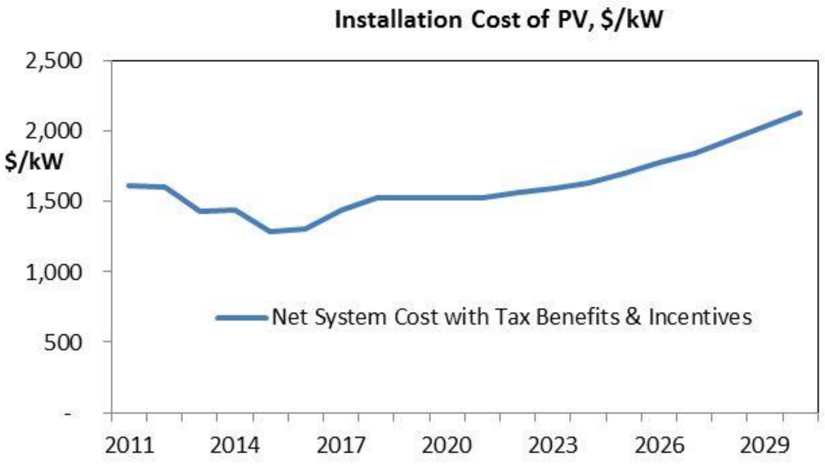

Figure 11 Net system cost of PV installation

As mentioned earlier, the failure rate of inverters are higher comparing to the PV ratings. Figure 12 shows the relation between the age of an inverter and probability of its failure data is used in optimization.

Figure 12 Failure rates of inverters

The University of Arizona is expected to grow in the future due to the campus wide developments; therefore, the demand of whole campus is expected to increase yearly as shown in Figure 13 in which the blue color shows UA utility demand. Due to the expected PV panel installation, the net demand would be less that is shown as green in the figure. Figure 13 shows that even though the total demand of the campus will increase in the future, the net demand would keep almost the same. Intuitively, the installation of PV panels makes the net demand of UA stable.

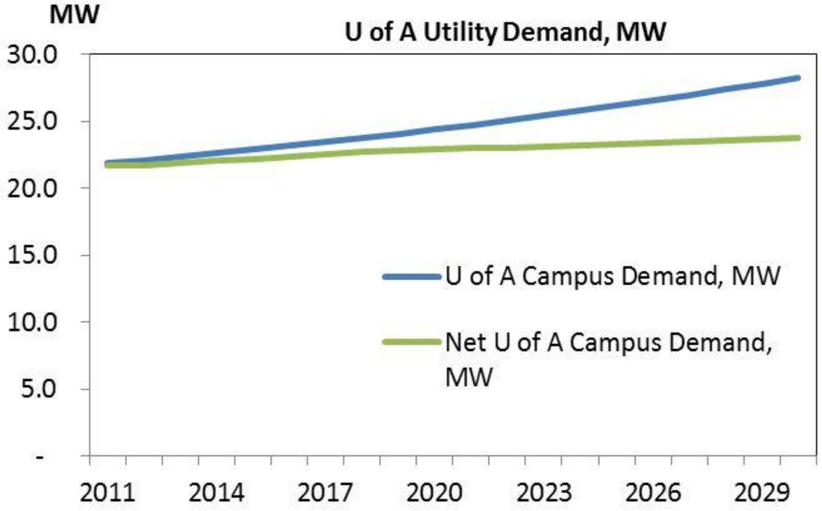

Figure 13 Demand profile of UA for next twenty year

Arizona is one of the states that the federal government challenges the utility companies to increase the utilization of renewable energy sources in 29 states. According to the Arizona Corporation Commission (ACC) Renewable Energy Standard, 15% of energy they utility company generates should be from renewable energy resources by 2025 (ACCRES 2006). Therefore, TEP makes policies to satisfy the requirement by ACC, which is shown in Figure 14.

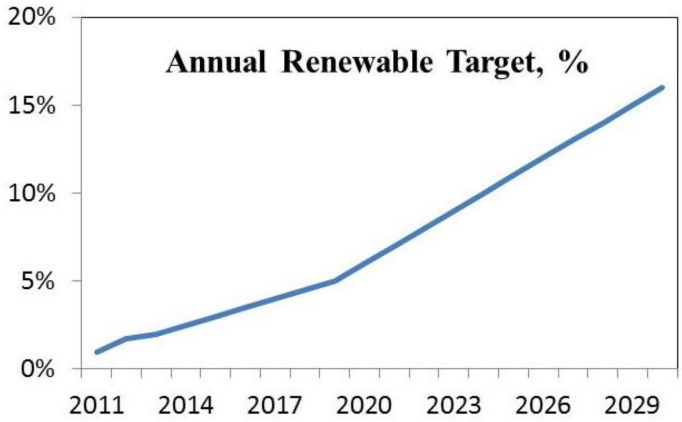

Figure 14 Annual renewable target for UA

The model is developed as described in earlier sections based on the data provided. The optimum solution is calculated using General Algebraic Modeling System (GAMS) programming. Codes in detail can be found in Appendix A. During the programming, all the constraints and objective function are changed to linear form which can be solved more accurate and faster. Table 3 shows the result from GAMS.

Table 3 Optimal Result of PV panel installation

Year	Buildings	Numbers of PV panels	Types of PV panels
2011	Second Parking Garage	770	Medium
	Health Center	397	
	Architecture	988	
	La Aldea Housing	983	
	Graham	951	
	Law Building	396	High
	Drachmann Hall	31	
2012	Computer Center	887	High
	Music Building	858	
	Second Parking Garage	81	
	Health Center	374	
2013	Education	411	High
	Roby Gymnastics	389	
2014	Bookstore	102	High
	Highland Parking	366	
	Six Street Garage	431	
	Eller	661	
2015	Biomedical Research lab	600	High
	Highland Parking	1000	
2016	Six Street Garage	1000	High
	Biomedical Research lab	640	
2017	Main Library	780	High
	Biomedical Research lab	900	
2018	Six Street Garage	778	High
	Eller	942	
2019	Tyndall Garage	760	High
	Highland Parking	1000	
2020	Bookstore	1026	High
	Medical Research	777	
	Health Center	54	
	Park Union	813	
	Museum North	770	
2021	Medical Research	1000	High
	Modern Language	770	
	Frank Sancet Field	760	
	ECE	696	
	Mining	294	
2022	Mining	401	High
	Physics Atmospheric	694	

	Biological West	693	
	Social Science	674	
	Nursing	673	
	McClelland Park	465	
2023	Centennial Hall	567	Medium
	McClelland Park	170	High
	Harvil	630	
	Apache	616	
	Science Library	605	
	Menial	586	
	Hall	248	
	Villa	525	
2024	Bookstore	404	High
	Hall	282	Medium
	Family and Consumer	525	
	Colonia	503	
	Posada	496	
	Pueblo	475	
	Coronado Hall	461	
	Astronomical	456	
	Civil Engineering	442	
	CESL	435	
	Anthropology	430	
	Chemistry	422	
	Psychology	418	
	Veterinary Science	382	
2025	Recreation Center	127	High
	Veterinary Science	35	Medium
	Kuiper	394	
	Roby Gymnastics	3	
	Biological Science	373	
	Cochise	353	
	Heating and Refridgation	337	
	Math East	333	
	El Portal	310	
	Life Science South	309	
	Facilities Shop	307	
	Communication	300	
	Engineering	293	
	Astronomy	286	
	Ica Stadium Restrooms	280	
	Forbes	276	
	Pharmacy	276	
	Art	275	
	Chemical Science	274	
	Environment and Nature Resource	268	

	Speech and Hearing	265	
	Old Main	250	
	Learning Service	241	
	Sonora Hall	191	
	Arizona Hall	160	
2026	Main Library	1960	High
	Drachman Hall	1038	
	AME	1023	
	Math Teaching lab	99	Medium
2027	Optical	1113	High
	Arizona Health Sciences Center	3087	
2028	MCKALE MEMORIAL CENTER	3240	High
	Recreation Center	1080	
2029	Park Garage	2221	High
	Cherry Garage	2189	
	Drachmann Hall	70	
2030	Student Union	1546	High
	Tyndall Garage	1891	
	Eller	295	
	Law	868	

Figure 15 shows the result of 10th year installation plan. Yellow part denotes the suitable places to install PV panels which can make the total profit maximum. It contains all the previous installation before the 10th year.

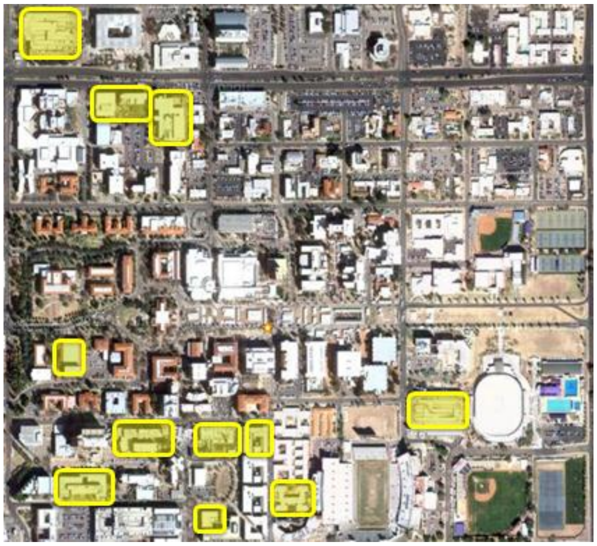

Figure 15 Result of Year 10 from Optimization

5.3. Sensitivity analysis

In order to study the effect of parameters on the results, several sensitivity analyses are performed to investigate the effects of panel output powers, utility rate, tax credit and incentives. Some of the results are given below.

Effect of utility rate

Utility rate changed every day according to the price of coal, oil, and other things. Figure 16 shows the price of oil in the past 30 years. According to the Figure 16, it is understood that the price of oil would increase rapidly in the future. Therefore, sensitivity analysis based on utility rate is performed and results are shown in Table 4.

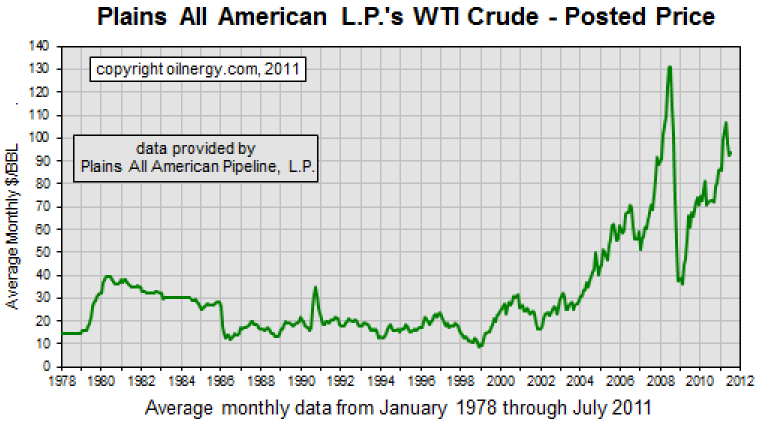

Figure 16 Price of oil in the past 30 years **(Plains All american Pipeline, L.P n.d.)**

Table 4 Sensitivity Analysis based on Utility Rate

Increment	0	10%	20%	30%	40%	50%	60%	70%	80%
Total Cost (million$)	28	28	28.3	32.2	32.3	32.4	32.4	32.2	32.2
Total Profit (million$)	-13.8	-12	-10.5	-8.78	-6.84	-5.17	-3.28	-1.32	0.51

Table 4 shows that the total cost doesn't change a lot even though the utility rate increased by 80%. However, the total profit would increase linearly with utility rate. If the utility rate increased by 80%, the total profit would become positive.

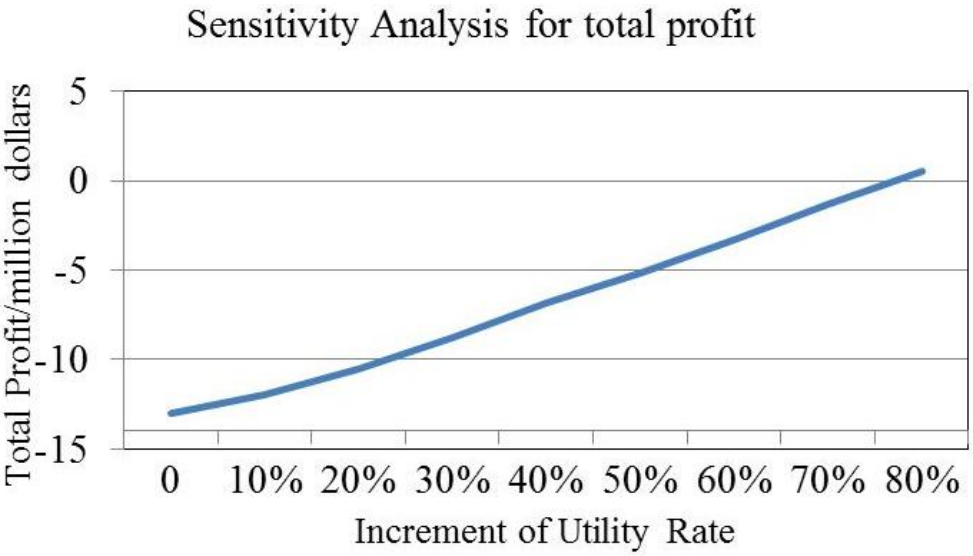

Figure 17 Increase of Total Profit with Utility Rate

From the figure above, it is known that with the increment of utility rate, the total profit from the installation would increase linearly. Once the increment exceeds 80%, the total profit would be positive which means that the investment would get benefit within 20 years. The result would be helpful for consumer since consumer can determine whether they will invest on solar panel installation according to different utility rate.

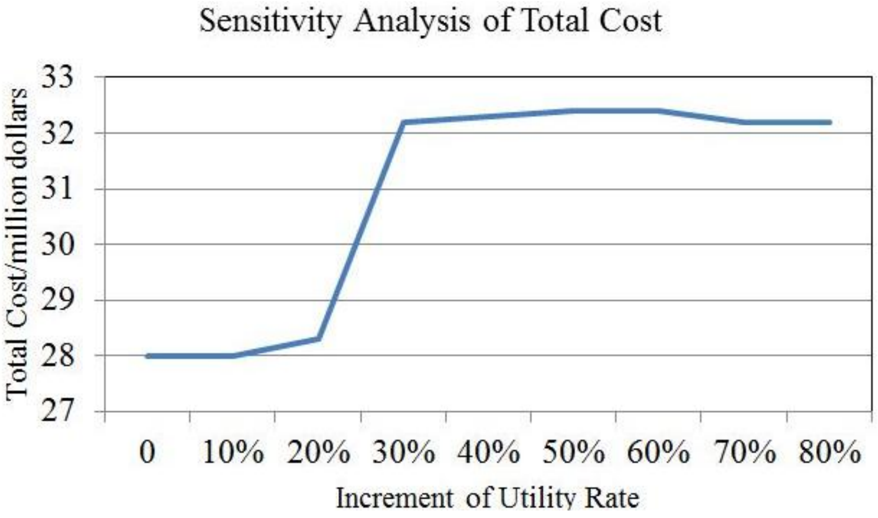

Figure 18 Changes of Total Cost with Utility Rate

Effect of Efficiency

With the development of technology, the efficiency of PV panels would increase in the future. However, it seems that the increment of efficiency doesn't influence the total profit as much as utility rate. Table 4 shows the effect of efficiency.

Table 5 Sensitivity Analysis based on Efficiency

Increment	0	10%	20%	30%	40%	50%	60%	70%	80%
Total Cost (million$)	28	26.4	24.7	27.3	28.8	32.2	34.4	36.6	39.1
Total Profit (million$)	-13.8	-12.1	-10.4	-9.31	-8.77	-7.55	-6.71	-5.96	-5.16

6. Simulation Module

Simulation module models given electric power distribution network and investigates the impact of PV installations on voltage profile through simulation. This module uses PowerWorld Simulator® program which is developed for power flow studies. The main functionality of this module is developing the simulation model of electric power distribution network from one-line diagram and simulating with the current and future PV generations. Simulation also calculates the bus (PV and load connection point) voltage and checks if it is within the limits of ±5% of 1 p.u. The amount and location of PV generations are defined by the previous GIS and optimization modules and used as an input for this module.

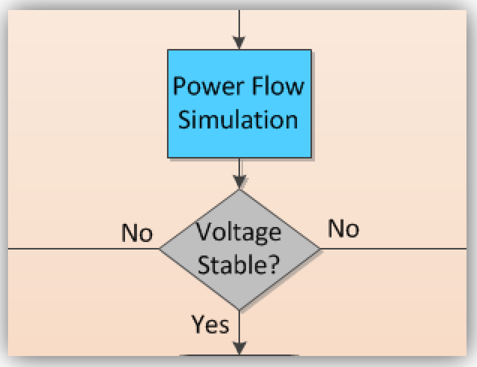

Figure 19 Simulation module in the framework

PowerWorld Simulator® program (PowerWorld Corporation n.d.) that uses one-line diagram, animated power flow and counter plots for voltage profile is used in this module. It also has the capability of time-step simulation for one day data simulations to investigate the effect of PV intermittency. Power flow study is a numerical analysis tool that uses one-line diagram and per-unit notations to analyze steady state operation. It calculates all the bus voltages and power flow through the distribution lines for over loading the lines (Narayanan 2010). Therefore, this program is selected to analyze PV installations in twenty year.

The objective of this module is to analyze the steady state performance of UA distribution network with and without the additions of current and future PV generations under different conditions such as cloudy and sunny day. It simulates yearly PV installations for twenty years and checks the voltage of each bus after each year installations to make sure that PV installation does not have negative effect into the system.

6.1. UA campus distribution system

One-line diagram of UA distribution network is modeled in PowerWorld (PW) simulation program. Partial campus distribution network[4] is re-drawn in PW. Typical distribution system data including cable, transformer specifications and partial campus network are used for circuit parameters. UA Facility Management provided four existing PV installation information is added to the distribution network modeling. Following section explains details of the data and UA distribution network.

6.2. Current PV installations in UA and distribution system map

UA distribution system currently has four PV installations with the total generation of 665 kW. The specifications of these installations are listed in Table **6**.

Table 6 UA PV installations

Location	# of Panels	Total generation
Location A	352 Panels	75.68 kWdc
Location B	1472 Panels	316.48 kWdc
Location C	128 Panels	27.52 kWdc
Location D	1168 Panels	245 kWdc

---

[4] One-line diagram is provided by Tucson Electric Power (TEP)

TEP provided one-line diagram of UA distribution network that shows the physical locations and electrical connections of the loads, transformers, switches and feeders. Figure 21 shows the one-line diagram. The campus is divided into two parts and both are supplied from TEP with different feeders. The two networks are connected to each other through a single feeder to supply loads. All the loads and transformers are identified with their connection configuration and lengths of the feeders are measured using AutoCAD software to use for the cable impedance calculations. The distribution cable data presented in (Narayanan 2010) and in Table 7 are used for impedance calculations. PV generators are connected right next to the loads that represent buildings in the campus. The amount of PV generations and their installation locations are calculated by the optimization module and are inserted as power generations in PowerWorld. PV generations are modeled as conventional generators in PowerWorld, however, automatic voltage regulation (AVR) and automatic generation control (AGC) are disabled since PV generation has a constant active power injection. Reactive power injections of the PVs are considered as zero since reactive power injections of inverters are not become a standard yet. The conventional generator that represents PV generation is used as a combination of PV and its inverter. Figure 20 depicts the PowerWorld model of the UA campus distribution network.

Table 7 Cable specifications

Size (AWG)	Resistance (Ω/kft)	Reactance (Ω/kft)	Capacitance (µF/kft)
#1/0	0.127	0.099	0.055
#2/0	0.102	0.097	0.059
#4/0	0.0635	0.092	0.07
#350	0.0385	0.085	0.085
#500	0.027	0.082	0.098
#750	0.018	0.077	0.116

6.3. Load and PV generation data

The buildings in the UA campus are considered as loads in the simulations. Due to the difficulties of accessing each building demand data, typical university building electricity consumption data that are publicly available are used to estimate the building load data (A. S. University n.d.), (P. S. University n.d.), (Itron n.d.). Some of the building consumptions are estimated based on a reference building data and considering the size and type of the building, the electricity consumptions are estimated. Figure 22 shows the daily electricity consumption of building that is used as base data (research building) data (A. S. University n.d.).

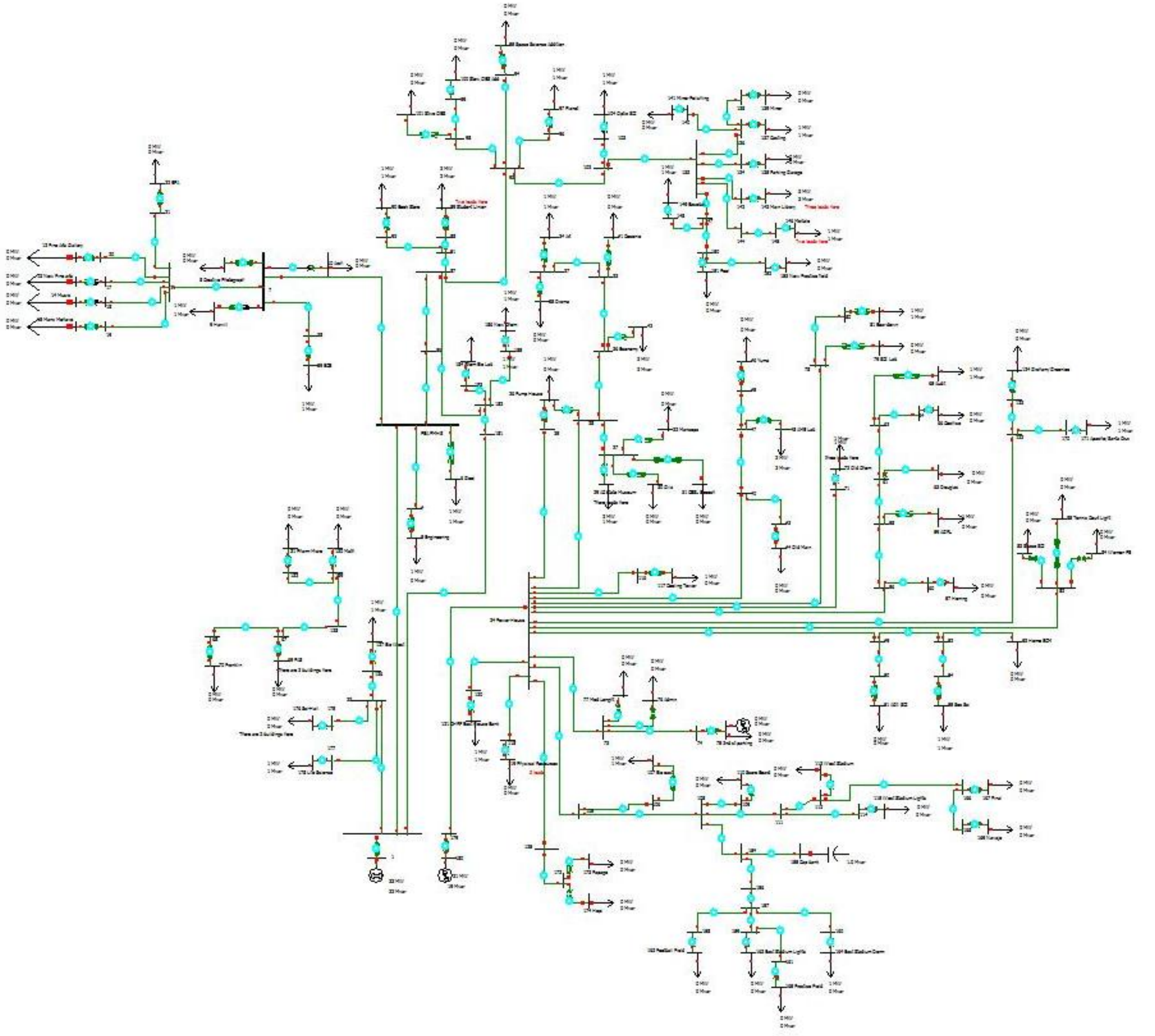

Figure 20 PowerWorld campus model

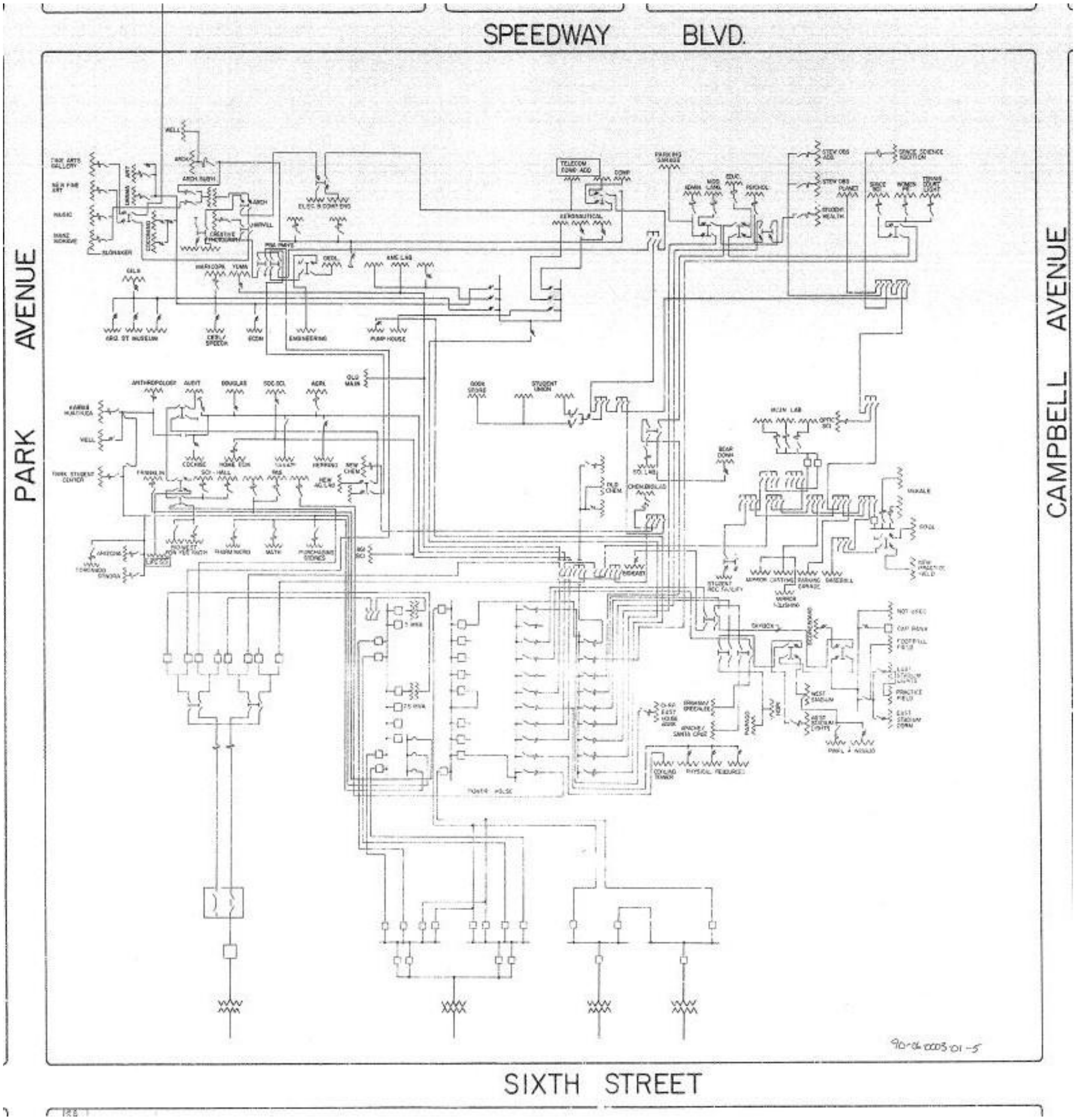

Figure 21 UA campus distribution network

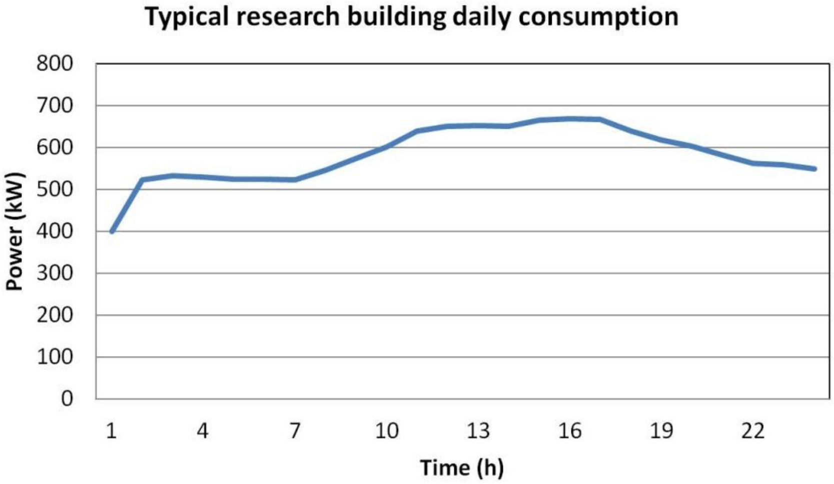

Figure 22 Typical research types building daily consumption **(A. S. University n.d.)**

The number of PV panels and the amount of total generation is defined by the optimization module. However, this amount is only the maximum power of the PV output. One day PV generation data is needed for time-step simulation which simulates twenty four hour generation and consumption. Daily PV generations data from TEP test yard (Photovoltaics at University of Arizona n.d.) is used for time step simulations. Typical sunny and cloudy day data can be downloaded in 1-sec to 1-hour time intervals. The amount of PV generation calculated by optimization module is considered as the maximum amount and daily PV generation is duplicated for simulations. Figure 23 shows 1-sec interval field recorded data.

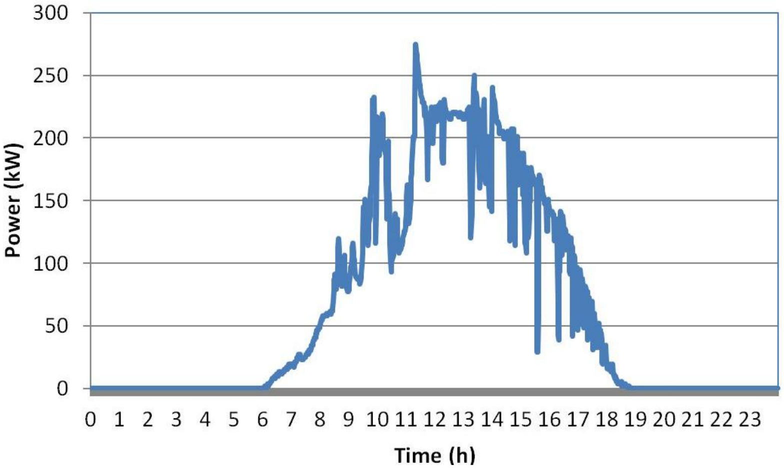

Figure 23 PV generation for August 1

6.4. Simulation procedure and results

Simulation has the following steps:

- UA distribution network is run with the existing PV installations in the campus to make sure that the PowerWorld model works without any voltage violations.
- The amount and location of PV generation coming from optimization module inserted in to the PW model. PV generations are connected to the same node with the load that represents the building that PV is installed.
- Simulation run just one time for steady state that represents the maximum generation and demand case.
- Bus voltages are checked to confirm that if they are within the range of ±5% of 1 p.u. If the voltage profile is satisfied, the simulation ends, if not then the re-allocation or battery module runs.
- Time-step simulation is run for the system with PV additions. PV generation amount defined by optimization module is used as the maximum amount of the generation and one day PV generation data is produced. One day load profile is also loaded and the simulation is run. This procedure repeated for both sunny and cloudy days. If the voltage profile is within the range the PV installation for the specific location, then the simulation ends. If not, re-allocation or storage modules run.
- This procedure is repeats for each year installations until the voltage profile is satisfied.

A case study is implemented in order to run the simulation module. UA Distribution network is modeled in PW and run with the current PV additions in the campus. Voltage profile results are shown in Figure 24. All the bus voltages are within the limit of 1±0.05 p.u. PV installation for one of the buildings is inserted and the future and an extreme case is simulated as low demand and high efficient PV generation. Although the reactive power injection is not become a standard yet, some constant reactive power provided by inverter is injected into the system. Daily PV generation is simulated for the PV installation and PW run for twenty hour. Voltage profile results show an over voltage for the PV connection bus. The re-allocation module is used as a solution method and some of the PV generation is moved to another building and the over voltage problem improved. Bus voltage of PV connection point before and after re-allocation can be seen in Figure 25 and Figure 26 respectively.

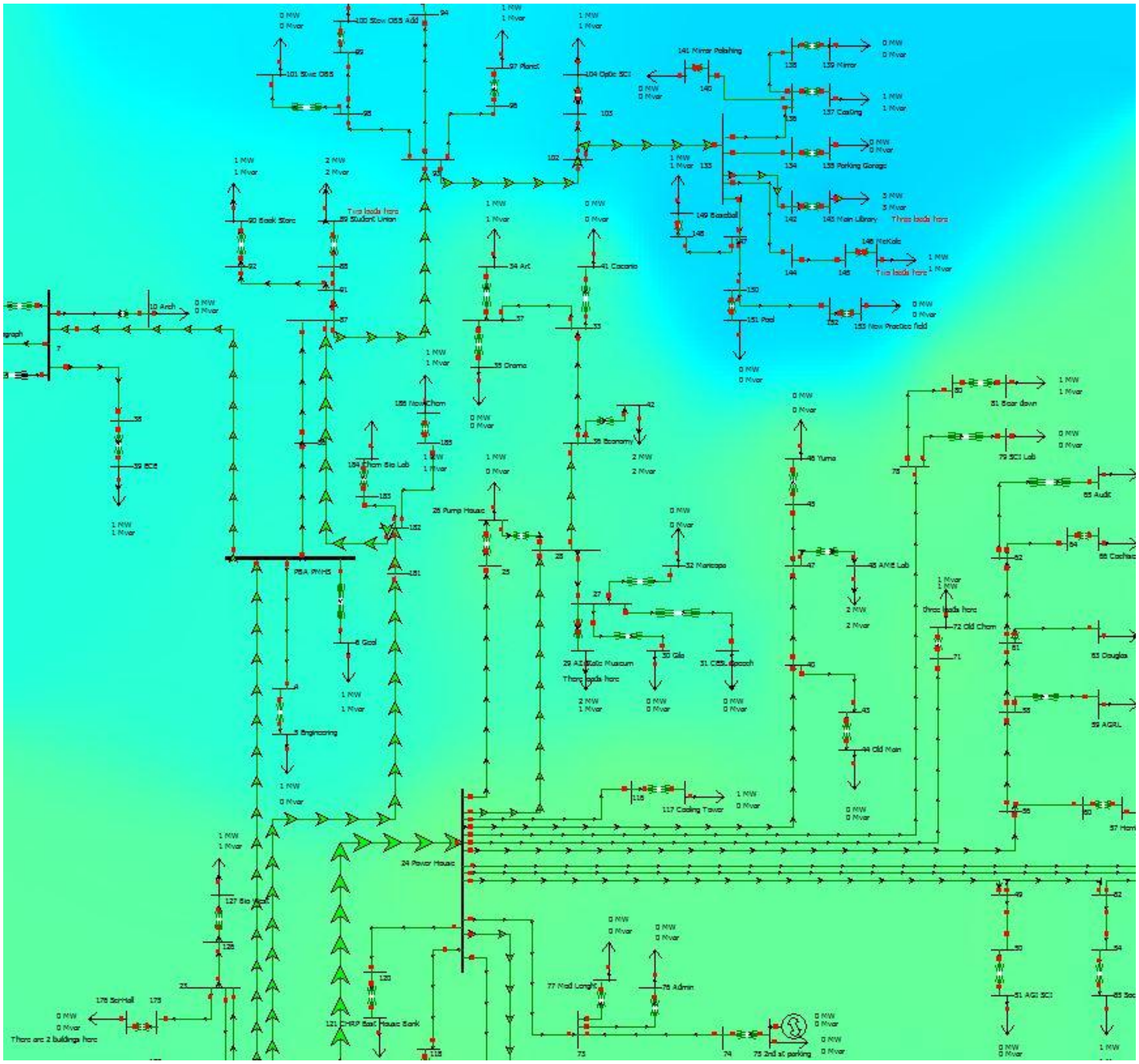

Figure 24 Voltage profile of campus distribution network

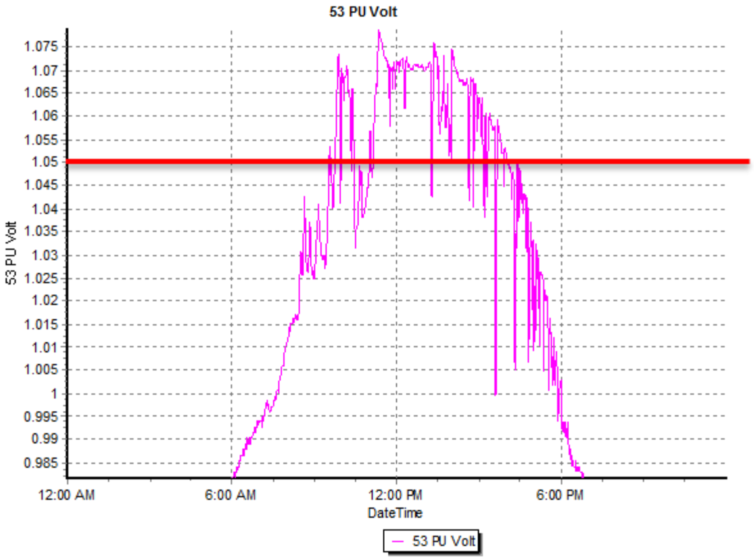

Figure 25 PV connection node voltage

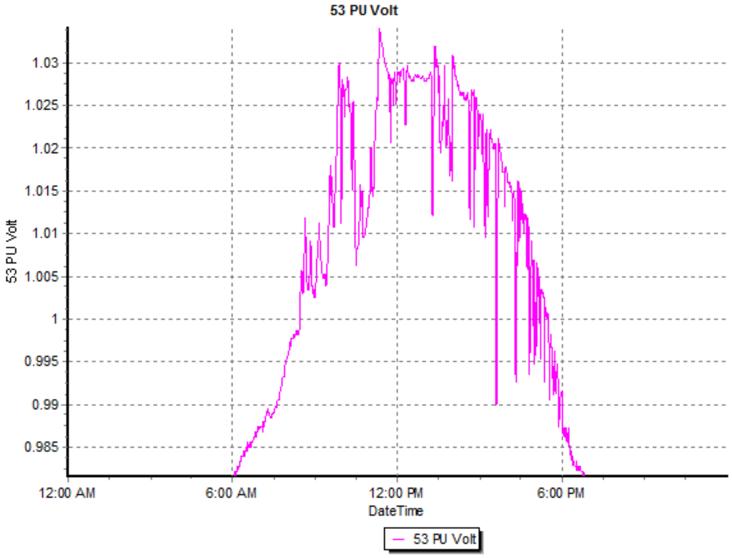

Figure 26 PV connection node voltage after re-allocation

6.5. Re-allocation and storage implementations in simulations

If the voltage profile is not satisfied through simulations, optimization module suggested PV generation for specific building is not appropriate for installation. This framework proposes two solutions to install the PV with in the voltage limits: re-allocation and storage. The details of these modules are explained in the related sections. Re-allocation means in PowerWorld is that the PV generator is removed from the current location and placed in another location with new amount both are defined by re-allocation module. Storage addition in PowerWorld is realized by adding additional load element which has both + and – (that represents charging and discharging) capability as shown in Figure 27.

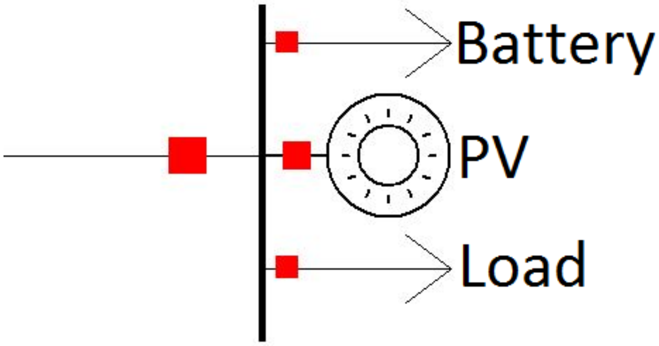

Figure 27 Storage module implementation in simulations

7. Re-allocation Module

Although the economical and geographical concerns are important factors for the integration of DGs into power grids, technical considerations are often viewed as a critical element affecting new installation decisions. The connection of distributed generation into the grid may influence the stability and quality of power system such as voltage profile. Distribution systems are traditionally passive and designed to operate with unidirectional energy flow unlike the transmission systems that have two-way power flow. DG makes the distribution system active and bidirectional since DG generations are injected into the system. This bi-directional power flow causes some violations in voltage profile (Hemdan and Kurrat 2008).

Voltage profile results from simulation module suggest making changes on PV installations defined by optimization module for specific year. One of the proposed solutions to keep the voltage profile within the limits is re-allocating the PV installations. The Re-allocation Module presented in this section explains in detail how the PV installations are modified both in capacity and location. Module uses a rule based approach presented by (H. L. Willis 2000) that is briefly explained in this section. A case study is presented to show the applicability of the Re-allocation Module.

7.1. Optimal placement of DG on a radial feeder

In order to reduce the impact of inappropriate voltage profile, a rule of thumb is investigated for changing the PV location that causes over voltages. It is presented in (H. L. Willis 2000) that "2/3 rule" can be implemented for a feeder that has uniform load distribution and DG installations. This rule uses a zero point analysis and capacitor placement method as an approach and can be found in detail in (H. L. Willis 2000). The "2/3 rule" suggests that if one DG exists in a feeder, the best DG size is 2/3 of the total load of this feeder and the best location is 2/3 of the length of this feeder to minimize the impact on protection, voltage regulation and loading. The graphical display of the rule is shown in Figure 28. Figure shows two-thirds rule applied to DG placement. A 2.66 MW unit located 2/3 distance out on the feeder minimizes shaded area comparing the shaded area before DG installation.

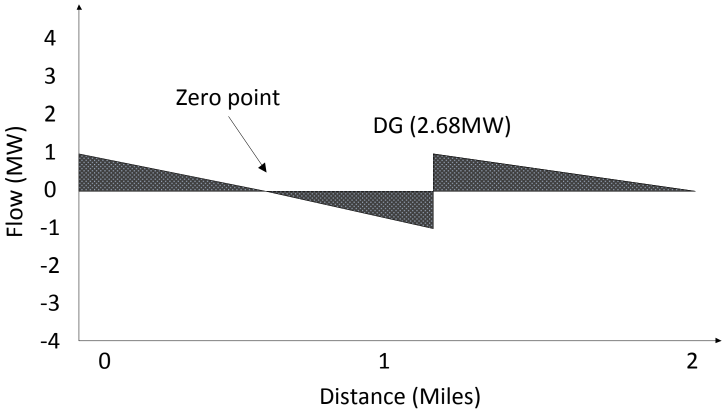

Figure 28 DG installation example

The general form of "2/3 rule" that determines the optimal locations for N DG resources for uniformly loaded a feeder with total load P is as following. (H. Willis 1997):

$$\text{Locations} = \text{n}\,.\frac{2}{2\text{N}+1}.\,\text{L from the substation} \qquad (17)$$

$$\text{for n} = 1, \dots, \text{N}$$

Based on this rule, the best two-DG location solution can be calculate as 2/5 and 4/5 of the distance from the substation. In the same way, the size of each DG is calculated as:

$$\mathrm{DG\ size} = \mathrm{n}\,.\frac{2}{2\mathrm{N}+1}.\,\mathrm{P} \qquad (18)$$

$$\text{for } \mathrm{n} = 1, \dots, \mathrm{N}$$

7.2. Procedure to find the optimal location of DG on a radial feeder

A Re-allocation method is established considering the “2/3 rule” as a reference. The objective here is to re-allocate the PV that causes voltage instability and assure that voltages along the feeder are in acceptable range of ±5%. The procedure to determine the optimal location to place PV on a radial feeder is given as follows:

1. Acquire the size and location of PV that causes voltage instability from simulation module.
2. Count total number of PVs along the feeder from simulation module as *N*.
3. Obtain the size of each *N* PVs from optimization module as *S(n)*.
4. Receive the roof capacity of all buildings along the instable feeder from GIS module.
5. Implement (1) to calculate location of each of *N* PVs as *L(N, n)*.
6. Move each of *N* PVs, around point *L(N, n)* and find the closest building which has minimum roof capacity of *S(n)*.
7. If all the PVs can be installed to buildings that satisfy *S(n)*, then these buildings are the optimal places to install PV.
8. If there is at least one PV that could not place to an appropriate building, then increase *N* by one, divide the capacity of PV that causes voltage instability by two and repeat steps 5) to 8).
9. These steps are repeated unless the final installations satisfy the voltage profile.

It should be noted that integration of PV at a certain feeder has no effect on the other feeders (Hemdan and Kurrat 2008). Therefore, if one feeder has inappropriate voltage profile, changing the locations of PVs on this feeder does not cause voltage instability on other feeders, as long as the total size doesn’t change. Figure 29 shows the visualization of the rule implementation.

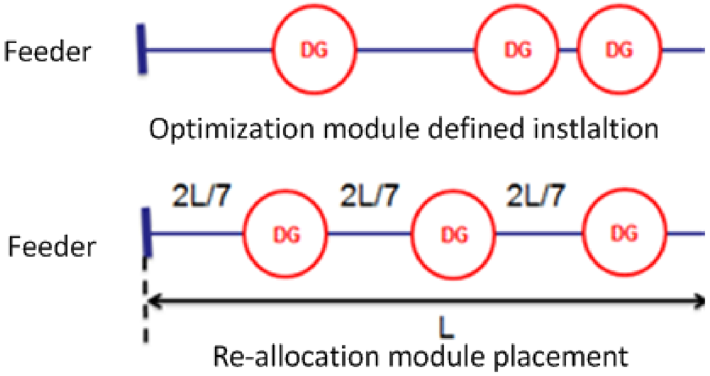

Figure 29 Sample re-allocation of DG based on 2/3 rule

The same procedure and the rule implemented into the campus model in PowerWorld simulations. Part of the campus model is selected and PV generations are added. A future case that has the low demand and high PV generation is studied. Three PV generations are intended to install in one feeder. However, this installations cause over voltage at some busses that PVs are connected. After going through the given procedures, PVs are placed in three locations that do not cause any over voltages. Figure 30 show the feeder configuration and Table 8 lists the voltage profile of buses before and after re-allocation rule. Results show that voltage profile is within the limits and the rule successfully implemented.

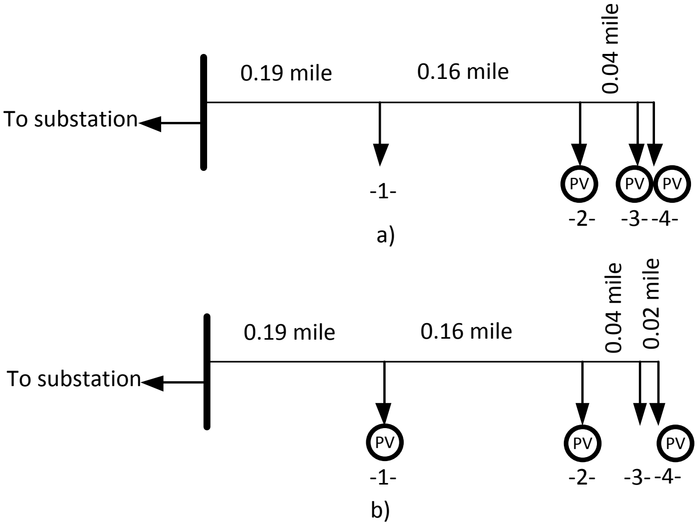

Figure 30 PV installations in simulation module a) before re-allocation b) after re-allocation

Table 8 Voltage profile of buses

Location	Voltage (before) p.u.	Voltage (after) p.u.
1	1.020	1.037
2	1.042	1.041
3	1.052	1.037
4	1.059	1.044

8. Storage Module

The second solution that this framework offers to keep the voltage profile within the limits is Storage module. This module uses storage elements installed next to the PV in order to support the PV generation or block the PV generation not to inject into the grid. Charging and discharging schedule defines the storage functionality which is not the focus of this framework.

In some cases, when PV generations are injected into the grid, power flow direction is reversed and over voltage happens and voltage exceeds the upper limit. (Agent 2009). In order to keep the voltage within the limits, (Nishikawa and Kazuhiko 2003) proposes to install battery banks to the same node that PV is installed. During the over voltage period, battery is charged and in the case of upper voltage or additional energy is needed, battery is discharged. This method is implemented in this framework and the size of the storage is defined through simulations by checking voltage profile. Since the storage implementation has a cost, a mathematical optimization method as an installing plan is proposed as explained in the next section.

8.1. Size of the storage

Re-allocation module presented a rule for optimal location and size for PVs. The size of the N PV installations on one feeder are identical and as follows

$$Size\ of\ each\ of\ DGs = \frac{2}{(2N+1)}.P \qquad (19)$$

where P is total load of the feeder. This formula is used to determine the size of storage as in the following procedure.

The procedure to determine the optimal size of storage that is used with PV installations to avoid over voltages is given as follow:

1. Find the size of voltage instable PV from simulation module as *S*.
2. Count total number of PVs along the feeder with instable PV from simulation module as *N*.
3. Obtain total load of the feeder from simulation module.
4. Use (1) to calculate the optimal size of PVs for *N* and *P* as *G*.
5. Calculate the size of storage as *S*-*G*.

8.2. Optimization

The goal of optimization is to decide which year is the best year to buy the storage unit with the size calculated above. The assumption in this model is that the electricity price of the grid is increasing by the time; on the other hand, the price of storage is decreasing. Although the energy needed must be bought from the grid in the delay time (installation year), the price of storage during this period becomes much less than present time prices so that delaying the installation become a beneficial decision.

If storage is bought in year *t*, all the energy in previous years is bought from the grid and in year *t*, the investment of buying the storage is done and from year t to the end of the project, year N, energy E (τ) will be bought from the grid where E (τ)< E(τ).

$$C(t) = \sum_{\tau=0}^{t} E(\tau)P(\tau) + I(\tau) + \sum_{\tau=t+1}^{N} \left[\bar{E}(\tau)P(\tau) + \left(E(\tau) - \bar{E}(\tau)\right).\alpha(\tau)\right] \qquad (20)$$

$C(t)$	Cost in year *t*
$E(\tau)$	Energy usage in year τ without having storage
$P(\tau)$	Price of energy in year τ
$I(\tau)$	Investment cost of buying storage in year τ
$\bar{E}(\tau)$	Energy usage in year τ after buying storage
$\alpha(\tau)$	Constant

The storage will be bought in a year which has the local minimum cost,

$$C(t-1) > C(t) < C(t+1) \tag{21}$$

9. Conclusions

In this work, a framework based on simulation and mathematical-based optimization has been developed to decide the best locations and capacities for PV installations with storage units. This tool covers various topics in one program, such as:

- profit maximization
- electricity stability
- emission factors.

Framework includes different modules and each module has its own software for analysis. All of these modules can run together or divergent so that the application area of this tool becomes broader. University of Arizona campus is selected as case study for the framework and all the modules are implemented. Results of the studies show that this framework is

- a complete tool that evaluates many aspect for PV installations
- a tool that considers economics and technical side of PV systems
- a program that utilizes different software
- a proposal for long-term installation strategy
- independent from the application area, hence, it can be applicable to both campus type areas and single buildings

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11. Appendix A

```
$TITLE AzSMART net cost
* 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026,
2027, 2028, 2029, 2030/
$onsymxref

SETS
   T year time period of 2010-2030 /0 * 19/
   m Buildings /1*80/
   K Type of pannel based on efficiency/Low,Medium,High/
   i  /1*3/
   j  /1*2/
;
ALIAS(T,F);
PARAMETERS
        e(K)  KW power of panel type K
/
        Low       0.08
        Medium     0.15
        High      0.25
/
*         Ca total target/14000/
        C(m)  Number of panels cam be installed in buiilding m or capacity of building m
/
1       3088
2       3240
3       1546
4       1532
5       2740
6       2651
7       2366
8       2221
9       2209
10       2189
11       1898
12       1777
13       1271
14       1207
15       1140
16       1139
17       1023
18       988
19       983
20       951
21       887
22       858
23       851
24       825
25       813
26       770
27       770
28       2140
29       760
```

```
30      696
31      695
32      694
33      693
34      674
35      673
36      636
37      630
38      616
39      605
40      586
41      568
42      530
43      525
44      525
45      503
46      496
47      475
48      461
49      456
50      442
51      435
52      430
53      422
54      418
55      417
56      411
57      394
58      392
59      373
60      353
61      337
62      333
63      310
64      309
65      307
66      300
67      293
68      286
69      280
70      276
71      276
72      275
73      274
74      268
75      265
76      250
77      242
78      191
79      160
80      99
/
        UR(F) anual Utility Rate at time T(c per KWh)
/
        0 7.01,1 7.39,2 7.60,3 7.93
        4       7.98
```

```
        5      8.19
        6      8.45
        7      8.62
        8      8.91
        9      9.06
        10      9.32
        11      9.43
        12      9.59
        13      9.67
        14      9.85
        15      10.09
        16      10.36
        17      10.54
        18      10.86
        19      11.09
/
       IRC(F) ($ per KW) Inverter replacement cost(1.02 times cost of previous year)
       /
       0 0
       1 400
       2 408
       3 416
       4 424
       5 433
       6 442
       7 450
       8 459
       9 469
       10 478
       11 488
       12 497
       13 507
       14 517
       15 528
       16 538
       17 549
       18 560
       19 571
       /
       P(F)  %Failure rate of inverters of age K(percentage of inverters with age k which need replacement)
       /
       0 0
       1*9 .01
       10 .02
       11  .05
       12*13 .10
       14 .15
       15 .50
       /
      L(T)  (KW)Lower constraint. the minimum number of KW power that must be installed each year.
/
       0 720
       1 550
       2 200
       3 390
      4 400
```

```
      5 410
      6 420
      7 430
      8 440
      9 860
      10 880
      11 900
      12 930
      13 960
      14 990
      15 1020
      16 1050
      17 1080
      18 1120
      19 1150
/
   TIC(T) Technology Innovation Curve (percent Input)
/
       0*7 .948
      8*11 1
      12*14 1.01
      15*17 1.02
      18*19 1.025
/
   UI(T)  Utility Incentive ($per KW input)
/
      0  2750
      1*2 2500
      3*4 2250
      5*19 2000
/
 FTC(T) Federal Tax Credit in year T (%)
/
      0*5   0.3
      6 .15
/
  STC(T) State tax credit(%)
/
   0*19 .05
/
 NSC(T,K) net system installation cost per KW with tax benefits & incentive for time period T and panel(6500$ per KW 5000 4000)
 IC(T,K)
;
IC('0','High')=6000 ;IC('0','low')=5000 ;IC('0','medium')=5634;
LOOP(T,IC(T+1,K)=IC(T,K)*TIC(T+1)) ;
LOOP(T,NSC(T,k)=(1-FTC(T)-STC(T))*(IC(T,k)-UI(T))) ;
SCALARS
      ASH  annual sunny hours /1750/
      r   Discount Factor  /0.08/
      CtD Cent to Dollar/.01/
      dr derating factor /1/
;

Integer VARIABLES
     n(T,K,m)           Number of panels must be installed at year T and Type K on building m
```

```
BINARY VARIABLE
     X(j,T,K,M)
     Y(t,k,m)
VARIABLES
     TCinvestment      total investement cost
     TCOparatMmaint    total maintenance cost
     TCOST             total cost
     TCreplacement     Total cost for replacing failed inverters
     TBENEFIT
     TOTALPROFIT
     Ins(T,K,m)
;

EQUATIONS
     TCinvestmentEQ                defines total investement cost of solar system
     TCreplacementEQ
     TCOparatMaintainEQ
     TCOSTEQ                       defines total cost up to T20
     Capacity(m)
     LCON(T)
*        Low
     OBJ
     TBENEFITEQ
     Economy1EQ(T,K,M)
     Economy2EQ(T,K,M)
     Economy3EQ(T,K,M)
     InsEQ1(t,k,m)
     InsEQ2(t,k,m)
     Eqx(t,k,m)
     Yeq(t,k,m)
     Yeq2(t,k,m)
;

n.up(t,k,m)=4000;

UR(F)= UR(F)*CtD;

Capacity(m)..SUM(T,SUM(K,n(T,K,m)))=L=C(m);

LCON(T)..dr*SUM(m,SUM(K,e(K)*n(T,K,m)))=G=L(T);

*Low..sum((t,k,m),e(k)*n(t,k,m))=g=Ca;

Economy1EQ(T,K,M)..e(K)*n(T,K,m)-1000*(1-X('1',T,K,M))=L=250*X('1',T,K,M);

Economy2EQ(T,K,M)..e(K)*n(T,K,m)=G=250*X('2',T,K,M);

Economy3EQ(T,K,M)..e(K)*n(T,K,m)=L=1000;

InsEQ1(t,k,m)..Ins(t,k,m)=g= 5000*y(t,k,m)+NSC(t,k)*e(k)*n(t,k,m)-100000000*(1-X('1',T,K,M));

InsEQ2(t,k,m)..Ins(t,k,m)=g= 5000*y(t,k,m)+0.7*NSC(t,k)*e(k)*n(t,k,m)-10000000*(1-X('2',T,K,M));

Yeq(t,k,m)..y(t,k,m)=l=n(t,k,m);

Yeq2(t,k,m)..n(t,k,m)=l=4000*y(t,k,m);
```

```
Eqx(t,k,m)..X('1',T,K,M)+X('2',T,K,M)=e=1;

TCinvestmentEQ..SUM(K,SUM(m,SUM(T,Ins(t,k,m))))=E=TCinvestment;

TCOparatMaintainEQ..(0.002)*SUM(F,SUM(T $ (ORD (T) LE ORD
(F)),SUM(K,SUM(m,Ins(t,k,m)))))=E=TCOparatMmaint;

TCreplacementEQ..SUM(F,IRC(F)/((1+r)**ORD(F))*SUM(T $(ORD(T)LE ORD(F)),P(F-ORD
(T))*SUM(m,SUM(K,e(K)*n(T,K,m)))))=E= TCreplacement;

TCOSTEQ..TCinvestment + TCOparatMmaint + TCreplacement =E= TCOST;

TBENEFITEQ.. dr*ASH*SUM(F,(UR(F)/(1+r)** ORD(F))*SUM(T$ (ORD(T) LE ORD (F)) ,SUM
(m,SUM(K,e(K)*n(T,K,m)))))=E= TBENEFIT;

OBJ.. TBENEFIT-TCOST =E=TOTALPROFIT ;

MODEL AzSMART /ALL/;
SOLVE  AzSMART USING MIP maxmizing TOTALPROFIT;
display n.L;
```

12. Appendix B

Pumped Hydroelectric

Key element of a hydroelectric (pumped hydro) system include turbine/generator equipment, a water way, an upper reservoir, and a lower reservoir. The turbine/generator is similar to equipment used for normal hydroelectric power plants that do not incorporate storage.

Pumped hydro systems store energy by operating the turbine/generator in reverse to pump water uphill or into an elevated vessel when inexpensive energy is available. The water is later released when energy is more valuable. When the water is released, it goes through the turbine which turns the generator to produce electric power.

Compressed Air Energy Storage

Compressed air energy storage (CAES) involves compressing air using inexpensive energy so that the compressed air may be used to generate electricity when the energy is worth more. To convert the stored energy into electric energy, the compresses air is released into a combustion turbine generator system. Typically, as the air is released, it is heated and then sent through the system’s turbine. As the turbine spins, it turns the generator to generate electricity.

For larger CAES plants, compressed air is stored in underground geologic formations, such as salt formations, aquifers, and depleted natural gas field. For smaller CAES plants, compressed air is stored in tanks or large on-site pipes such as those designed for high-pressure natural gas transmission (in most cases, tanks or pipes are above ground)

Flywheels

It is an inertial energy storage device that couples a motor generator with a rotating mass to store energy for short durations. Concept of rotational energy is used in the Flywheel energy storage. It stores the energy by using the rotor to a very high speed. The energy is converted back by slowing down the flywheel in it. Flywheels are charged and discharged via a combined motor/generator. The combined set draws power provided by the grid to spin the rotor of flywheel. During voltage sag condition or other power quality problems the motor/generator set provides power. The stored energy is in the form of kinetic energy. In the rotor it is transformed to DC electric energy by the generator. The energy is delivered at a constant frequency and voltage through an inverter. Flywheel rotors are usually constructed of speeds up to 21000 to over 48000 rpm. It is used to achieve very high power densities. Flywheels provide 1-25 seconds of ride-through time, and back-up generators are typically online within 5-25 seconds. Stored energy is proportional to the Flywheel's mass and the square of its rotational speed. The energy stored in a Flywheel given by the following equation.

$$\mathrm{E} = \frac{1}{2}\mathrm{I}\omega^2$$

Where I is the moment of inertia of Flywheel and ω is its rotational velocity (radians/second).
The moment of inertia is given by equation

$$\mathrm{I} = \mathrm{kMr}^2$$

Where M is the mass of the Flywheel, r is its radius and k is its inertia constant. The longer life, simpler maintenance, and slighter footprint of Flywheel systems are the advantages of Flywheel.

Batteries

Batteries are electrochemical devices which convert chemical energy into electrical energy during discharge time. Batteries are classified as secondary storage devices. Their operating conditions depend upon charging and discharging cycle. The first commercially available battery was the flooded lead-acid battery while the valve-regulated lead-acid (VRLA) battery is the latest development. It has low-maintenance, spill- and leak-proof and it is relatively compact. Batteries are constructed in a wide variety of capacities ranging from less than few watts to several megawatts.

Capacitors

Capacitor has two oppositely charged electrodes, separator electrolyte and current collectors. Capacitors have been used to store energy and supply short pulses of high power. The most important advantage of capacitor is the capability to supply high current pulses repeatedly for thousands of cycles. The batteries provide power only during the longer interruptions, reducing the cycling duty on the battery. Small super capacitors are commercially available to extend battery life in electronic equipment, but large super capacitors are still in development, the energy stored is related to the charge at each interface, q(Coulombs), and potential difference V(Volts), between the two electrodes. The energy E(Joules) is given by the following equations

$$\mathrm{E} = 0.5\ \mathrm{q}\ \mathrm{V}$$

$$E = 0.5\, CV^2$$

The following table represents the comparison between batteries and capacitors w.r.t. their energy density, power density, cycle life and discharge time.

Fuel Cell

Fuel cells are renewable energy sources. Fuel cell is an electrochemical conversion device. It transforms the chemical energy into continuous electrical energy. Fuel from the anode side and an oxidant from the cathode side are combined in the presence of electrolyte and generate electricity. It consumes reactant, which must be replenished. Fuel cells are stable and so many combinations of fuel and oxidant are possible. For example in hydrogen type cell hydrogen, hydrocarbons and alcohols are used as fuel and oxygen, air, chlorine are used as an oxidant. The regenerative fuel cell converts electrical energy into chemical potential energy charging two liquid electrolyte solutions. It is converted back to electrical energy on discharge time. It is a reversible electrochemical process in between two salt solutions. The fuel cell has discontinuous conduction performance advantage as well as cost of raw material in fuel cells is very low.

Electrochemical Batteries

Electrochemical batteries consist of two or more electrochemical cells. The cells use chemical reactions to create a flow of electrons-electric current. Primary elements of a cell include the container, two electrodes (anode and cathode), and electrolyte material. The electrolyte is in contact with the electrodes. Current is created by oxidation process involving chemical reactions between the cell's electrolyte and electrodes.

When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell's electrodes supply electrons(oxidation) while ions near the cell's other electrode accept electrons(reduction), to complete the process. The process is reversed o charge the battery, which involves ionizing of electrolyte. An increasing number of chemistries are used for this process. More familiar one include lead acid, nickel-cadmium(NiCad), lithium-ion(Li-ion),sodium.sulfur(Na/S), zinc/bromine(Zn/Br),vanadium-redox and others.