Site Location Suitability Analysis for a Smart Grid Network

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AMI	Advanced Metering Initiative
AOI	Area of Interest
BLM	U.S. Bureau of Land Management
CHP	Combined Heat and Power
CPUC	California Public Utilities Commission
DCU	Data Collector Unit
DRG	Digital Raster Graphic
FGDC	Federal Geographic Data Committee
FID	Feature Identification Code
MCLP	Maximal Covering Location Problem
NED	National Elevation Dataset
NRCS	National Resources Conservation Service
SCGC	Southern California Gas Company
USDA	U.S. Department of Agriculture
U.S.	United States of America
USGS	U.S. Geological Survey

Abstract

A smart grid is an energy grid network upgrade to a system that captures waste heat, adds detail and visibility to household monitoring techniques, allows for compatibility with remote alternative energy sources, and transfers data from meters to communication towers, also known as Data Collector Units (DCUs) using wireless technology. California is mandated to provide 33 percent of statewide energy from renewable sources by 2020. An energy network upgrade to a smart grid would facilitate the remote storage and transfer onto the grid that are necessary for solar and wind farms, which are often located far away from dense urban centers. Past research on smart grid development has focused on maintaining optimal meter to communications tower readings through analysis of distance to meters, spacing throughout a region, elevation and slope. Some site suitability research has focused on optimizing wind turbine placement so as to reach customer regions while simultaneously not offending nearby residents and staying clear of housing viewsheds. One particular power plant site suitability study used an ArcGIS weighted overlay analysis to return a score of one to 10 as a final site suitability predictor. This project incorporated ideas from each of these analysis approaches by including a viewshed analysis of meter-to-communication tower dynamics, communications tower site acquisition variables needed for placement objectives, and a pass/fail scoring system reflecting each variable. The site suitability tool meets the meter visibility objective of quantifying line-of-sight, nearest feature association, and distance between utility meters and communications towers. Three site acquisition objectives were considered: (1) pinpointing tower locations within 20 ft of a publicly-maintained street; (2) placing towers a minimum of ten feet from power lines for safety reasons; and (3) determining location(s) that are likely to avoid tree obstructions, so that radiation is sufficient to meet the needs of communication tower solar panels.

Chapter 1: Introduction

1.1 Background

There are few issues today that are of a more pressing concern than climate change and carbon emissions mitigation. The human carbon footprint is particularly acute when multiplied by overall population— over 7 billion and continuing to grow. The carbon footprint comprises the sum of all greenhouse gas emissions. One of the most significant contributors to greenhouse gas emissions is energy usage: recent statistics from the U.S. Environmental Protection Agency state that 39 percent of total energy consumed in the U.S. is from electricity consumed in homes and businesses (EPA 2013a, p. 1), the most significant of all energy footprints and easily exceeding the second highest demand, transportation at 27 percent. Furthermore, electricity consumption is responsible for 32 percent of total U.S. greenhouse gas emissions (EPA 2013b). In order to decrease the greenhouse gas emissions of electricity and prevent potential undesirable effects related to climate change, more efficient and less pollution-creating means of generating electricity— such as solar, wind, geothermal, hydrogen, and biofuel energy— have increased in popularity during the past decade (leading up to the time of this project). They have increased to the extent that California— perceived as a leader in U.S. renewable energy consumption— has committed to receiving 33 percent of statewide energy from renewable sources by 2020 (Redall and Groom, 2013). California has low per household energy usage numbers, ranking 47th in per capita energy consumption in the U.S (U.S. Energy Information Administration, 2013). The state ranked second in total electricity generation from renewable resources in 2011 and is responsible for 13.6 percent of the renewable energy power created in the U.S. California's concerns regarding climate change and the ecological footprint of electricity generation and use have been catalysts for smart grid deployment throughout many parts of the world.

Populations, particularly those as sizeable as that of the State of California, cannot commit to incorporating significant quantities of renewable energy into their supply without an upgrade to the current electricity system that allows remote solar and wind farms to feed into the overall grid. This must be accomplished in a means that is efficient but also allows the unused excess energy to be incorporated back into the grid easily. A smart grid can facilitate such an outcome through the creation of microgrids, or smaller versions of the centralized electricity grid, that accommodate Combined Heat and Power (CHP). Microgrids are able to mimic the capabilities of the overall energy grid, by generating, distributing, and regulating the flow of electricity to consumers (Kelly, 2010). They also carry greater capacity to accommodate remote solar, wind or biomass sources to not only be a part of the energy grid but also to collect energy waste by way of CHP systems (Farhangi, 2010). CHP is a means of generating electric power through units that are strategically located in a dispersed manner near specific facilities in need of energy supply. The process increases overall grid efficiency by producing both thermal and power output simultaneously (Naik-Dhungel, 2008), leading to a marked performance improvement over the electric and thermal-only systems in the traditional energy grid with a centralized power output structure.

A smart grid will also level out the erratic output tendencies of solar and wind farms by storing remote energy as well as making use of output collectively from multiple sources (Farhangi, 2010). The energy system allows for troubleshooting sources of power failure, pinpointing peak energy load times and locating inefficient appliances (Pataki, 2003). This troubleshooting occurs as a result of power generation occurring in a more distributed manner as opposed to a smaller number of large power plants located some distance from customers (Xia, Diuglas and Mandic, 2012). A distributed energy system is what allows microgrids— that are often powered by renewables such as wind and solar— to improve the balance within the overall network. For these reasons, a smart grid is a necessary predecessor to a human population that relies to any significant degree on renewable energy.

A smart grid upgrade of the standard electricity grid is also significantly more efficient with regards to energy use and power outage mitigation. By providing a two-way communication system, energy can be monitored for sources of high output, causes of energy failure, and individual issues within a home or business can be remedied. Previously, energy usage was recorded as a single value for a whole day, with no specification of individual contributions to output and no temporal aspect to monitoring. Only one-third of fuel energy was converted into electricity, waste heat was lost entirely in delivery, and almost eight percent of overall output was lost along transmission lines (Farhangi, 2010). Therefore, if renewable energy were taken out of the picture as a goal in California, a smart grid would still be valuable because it would improve the efficiency of the electricity grid.

A smart grid is a two-way communication system from the meter to a communication tower using radio frequency propagation. The communication tower records signal input from each meter a few times per day and that information is read by the utility company. Two-way communication allows for information transfer between utility companies and end users. The former then has the capability to distribute data about cost management, power outage potential as well as usage patterns and customers have the ability to send usage information and monitoring data that can be used by the utility company in determining current and future power needs to the provider (Kallitsis, Michailidis and Devetsikiotis 2011). Data sent across a smart grid energy system, furthermore, are converted into a code that cannot be read by others (Gould, 2013). Meter readings and customer usage records are transferred to the energy provider with no fear of the information being stolen or made available to the public, as utility company data safety and security measures are normally reviewed by the U.S. Department of Energy on an annual basis (Gould, 2013). A solar-powered DCU (Data Collector Unit) communications tower that plays a key role in these systems is demonstrated in Figure 1.

Figure 1: Smart grid DCU communications tower

Smart grids, therefore, offer potential benefits for data monitoring. In pre-smart grid energy systems, a meter reader would record data from a meter that outputs a summary of daily energy usage as one single total. There was no distinguishing what appliance and/or activity was responsible for specific shares in total daily usage, such as an inefficient refrigerator or air conditioner that is consuming greater quantities of energy than the new dishwasher. A smart grid would allow customers to log into an online account and view daily usage totals for individual appliances. In this way, a customer can pinpoint energy inefficiencies and troubleshoot the sources of high energy bills. Energy data monitoring includes the time usage occurred, power quality, power factor, spikes, individual power phases, grounding, and load shape (Pataki, 2003).

One of the most significant challenges for the utility companies is deciding how to place communications towers throughout a metropolitan area so that they are evenly spaced and such that no meter is left without a DCU which is able to read its signal. The challenge is fundamentally a geographic location-allocation issue for communications tower placement. Smart grid communication tower placement shares a great deal in common with wind turbine placement with regards to balancing the benefits vs. the disturbance. Pedersen and Waye (2004), for example, concluded that the proportion of respondents in a survey who were annoyed by wind turbine noise is higher than for other sounds coming from area sources at the same frequency levels, and are further impacted by the visual displeasure associated with wind turbines. Wind turbines are significantly larger and more often come in groups unlike smart grid communication towers, yet share similar aesthetic connotations in how populations perceive energy assets in their neighborhood.

There are site acquisition issues to contend with as well. The DCU must be placed in a public right-of-way, must be able to acquire sufficient solar radiation in order to operate a solar-powered communications tower, and must not offend neighborhood residents with a view of the communications tower. Residents often feel that the viewshed from their window is an important aspect of why they pay what they do for their home, and new towers will often generate complaints and calls to relocate communications towers. Development of a full smart grid, therefore, is a multi-criteria geographic location problem that attempts to provide service to residents and other consumers while avoiding direct placement in the vicinity of the housing units themselves.

In smart grid deployments, significant time and energy is devoted to achieving optimal communications tower placement based on site acquisition variables. The criteria accounted for in this project— distance to power lines, publically-maintained streets, and tree canopy— are accounted for either within a spatial photography analysis program such as Google Earth and/or via field visits. These procedures waste time, energy, resources, and capital that could be significantly alleviated with the advent of one or more site suitability tools. Furthermore, resources and time are devoted to troubleshooting meters in the field that are not communicating with nearby towers. A tool that places communication towers and also demonstrates which of these assets is visible from each individual meter would allow for specific meters to be called out that are in need of repairs or manual reads. It could also streamline analyses that are often redundant and allow for a filtering process in site selection that optimizes site locations and yet also incorporates site acquisition procedures into the analysis. A standard gas meter (left side) that was traditionally maintained by a meter reader and a smart grid utility meter (right side) are shown in Figure 2. A smart grid utility meter is a communications device attached to an existing analog meter that is battery operated and transmits a radio frequency signal in short bursts to the nearest communications tower (Southern California Gas Company 2014). The battery turns on for less than two minutes per day to allow for signal relay and lasts for up to 20 years.

Figure 2: Standard gas meter (left) and smart grid utility meter (right)

Wind and solar energy are important in mitigating future concerns regarding climate change. Few regions are more ideal for alternative energy than California. Renewable energy has grown by more than 120 percent since 1995 (Paine and Lewis, 2013), resulting in an 11.6 percent share of overall electricity generation in 2009 (Hochschild, 2013) and a statewide decree to achieve one-third of total electricity production by 2020 (Redall and Groom, 2013). These goals will be ushered into California through a smart grid system deployed throughout the state's five largest metropolitan regions.

The smart grid— as an upgrade to the current energy infrastructure— began in the 1990s with meters being read using a radio frequency recorded in a van that would drive through neighborhoods (Hastreiter, 1997). The new system of measuring electricity consumption using wireless technology holds significant potential for utility companies and customers alike, in improving the efficiency of our systems, supporting data analysis, and reducing ecological footprints. Utility companies would benefit from decreased gas costs and fossil fuel pollution output by eliminating the need to send meter readers into neighborhoods throughout metropolitan areas, and logging hundreds of thousands of miles onto company vehicles. Additional benefits associated with an elimination of manual meter reading could then be further realized, such as reductions in worker injuries related to accessing meters located on private properties. Meters may potentially be located underneath cast-iron lids, alongside or within homes. Repetitive lifting injuries, bee stings, dog bites, and repetitive motion injuries related to walking long daily distances are all potential scenarios that would result in company compensation to workers. A small utility company in Aiken, SC that services 40,000 meters paid out about $80,000 over a five-year period for worker compensation claims in the mid-to-late-1990s (Hastreiter, 1997). Workers compensation would certainly be significantly higher for a utility company in southern California servicing over 6 million meters. In northern climates, smart grids can provide an additional benefit of negating costs associated with weather-related risks. Sending meter readers in snow, ice, and freezing cold temperatures presents a risk to safety as well as company vehicles that need to navigate the difficult conditions.

1.2 Thesis Goals

GIS analysis is frequently used for site suitability studies to sort through the geographic placement considerations. With regard to energy assets, site suitability analyses often incorporate environmental variables, strategic placement in relation to other assets, and avoidance of significant structures— but it is not often that all of these variables are included into a single site suitability analysis tool. Energy companies may contain two separate departments that work on network deployment procedures— one for tower-to-meter analysis and another for ensuring that the governing bodies have no issues with the proposed locations. The best final sites are those locations which satisfy the criteria within both of these areas.

The overarching goal of this thesis project is to build a site suitability tool that can identify such locations. In order for a smart grid to operate, all utility meters associated with homes and residences must have a DCU within range in order to receive output signal bursts. This means that each meter must have a minimum of one communications tower that maintains line-of-sight to its location. Using this project tool, the job of individually reading meters—formerly carried out in the field by a technician— would now be achieved by way of communications towers strategically placed within a network. The real achievement, however, of such a project tool is in displaying which communications towers are within a specific range of each meter and whether or not each communications tower has visibility to individual meters. The tool should also allow for troubleshooting why a meter is not communicating with a DCU by comparing field results to original line-of-sight analysis so that the issue of non-visibility can be separated from other issues, such as meter hardware or unit placement issues. The secondary goals of proposing such a site suitability tool are to evaluate for the efficacy of ArcGIS's Observation Points tool and the effectiveness of using National Elevation Dataset heights compared to real-world field measurements (i.e. real-world visibility results). It was created to support the placement of a communications tower network, as a preliminary analysis tool for the identification of optimal sites, and as a troubleshooting guide to work in tandem with gas company field operations. The project tool maximizes ArcGIS's capabilities in predicting radio frequency dynamics despite the software platform's lack of a mechanism specifically designed for this purpose. In other words, it is a preliminary predictor of meter transmissions to communications towers without the ability to specifically measure the radio frequency gains and losses that occurs when radio waves pass through buildings, towers, and other high structures. Specially designed software would be needed in order to achieve more precise outcomes. The final objective for this project tool is to balance the previously stated goals related to meter-to-communications tower performance analysis with DCU site acquisition feasibility in designing the most effective yet realistic network model to provide coverage to all utility meters and to further rate this efficacy.

Smart grid deployment in today's utility industry relies on specialty software— such as EDX wireless— in order to run radio frequency analysis between meter and communications tower. EDX software incorporates variables such as decibel gain and loss, atmospheric absorption, ground conductivity, climate type settings, various model types that are applicable to numerous environmental and asset equipment scenarios, and includes a clutter data file containing specific heights of buildings and other structures within the built environment. Software such as EDX wireless, however, is restricted to a point-to-point analysis that lacks criteria for site placement decisions outside of a radio frequency analysis. The software also lacks the geoprocessing tools for data manipulation and analysis that are needed in various decision-making criteria. ArcGIS opens the smart grid network creation process up to a wide variety of data and processing techniques that allow for DCU placement based on proximity to real-world features. The most significant characteristics that EDX software offers as a perceived advantage over ArcGIS is the inclusion of clutter/buildings data, path gain and loss calculation, and a model that can be adjusted to local environmental variables. Each of these qualities can potentially be replicated in ArcGIS by the addition of heights into terrain data as well as the application of path loss equations that closely replicate local environmental conditions. The intention with this project tool is to introduce the possibility of closely replicating the radio frequency analysis capabilities of current industry standard software while improving on network placement logic by including several geographic variables into analysis procedures.

The objective for this project in regards to meter visibility was to build a network that covered as many meters as possible while using as few DCUs as possible but adhering to locations determined by building a grid. This objective was intended to be a preface to one of two techniques required in order to achieve complete meter coverage using the least number of DCUs possible: (1) manual modification of DCU positions in order to achieve the most optimal visibility placement while still meeting placement specifications (i.e. at the edges of publicly maintained roads); or (2) a location-allocation equation with associated geoprocessing procedures that singles out feasible regions, checks the visibility of each raster cell within the selected areas, and determines the optimal location for each DCU. Potentially extensive computing power as well as an adherence to placement specifications would be the most challenging aspects of a location-allocation analysis.

1.3 Study Area

The Advanced Meters project is a smart grid energy upgrade that will be deployed throughout southern California from late 2012 through 2017 (projected at the time of this thesis project). The overall project area stretches from the desert just east of San Diego all of the way to Morro Bay, a distance spanning approximately 400 miles and an area containing one of the largest population clusters in the U.S. Los Angeles County alone contained 9,818,605 people as of 2012 and is the most populous county in the U.S. (US Census Bureau, 2014). This thesis project focuses on a smaller region within the Advanced Meters Southern California territory— the City of San Luis Obispo— that is located approximately 150 miles to the northwest of Los Angeles near the California coast. San Luis Obispo County had a 2012 population of 276,443 (US Census Bureau, 2014a), with 46,377 of this total residing in the City of San Luis Obispo (US Census Bureau, 2014b). Figure 3 shows the project area within the City of San Luis Obispo, California. The Digital Raster Graphic (DRG) map sheets displayed in this map were compiled and published in 2001 and representing 1939 to 2001 as part of the USGS's periodic data modernization efforts.

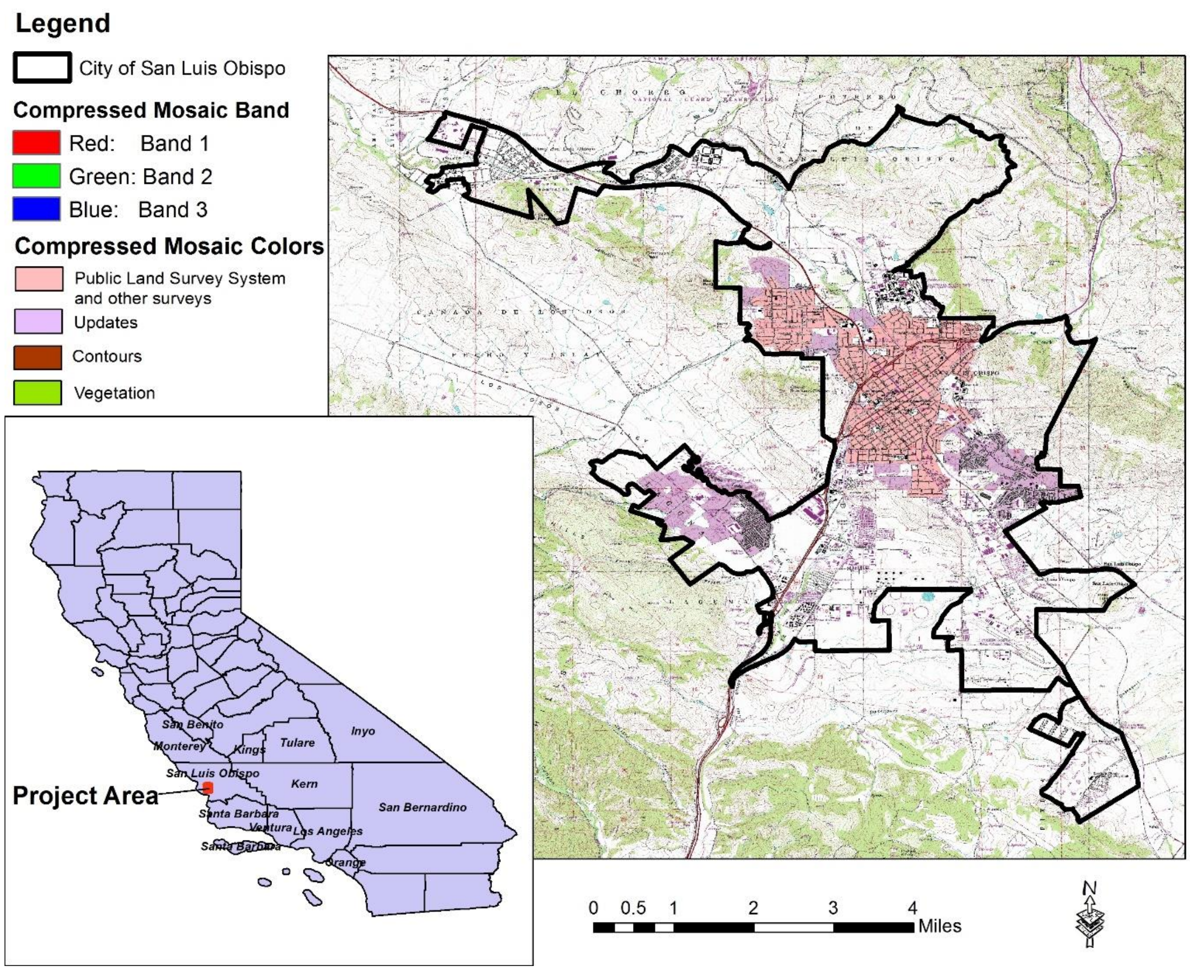


Figure 3: Map showing project study area

The Advanced Meters project seeks to connect 6 million meters operated by the Southern California Gas Company to towers that are spaced throughout the region in a manner that provides wireless coverage to all meters while also using the smallest number of assets. This feat can only be achieved by placing communications towers in locations that offer optimal visibility. The overarching goal of this thesis project was to demonstrate how GIS can be deployed to help advance this outcome, as demonstrated in the following chapters which cover related work (Chapter 2), the methods and data sources used to construct the tools (Chapter 3), the results— a description of the tool itself and the results of its deployment in the City of San Luis Obispo (Chapter 4), and an extended discussion of the role of GIS in such applications and some conclusions and suggestions for further work (Chapter 5).

Chapter 2: Related Work

There is a long tradition of using geographic information systems to support site suitability studies and several that have focused on electrical systems— both the power plants themselves and the above- and below-ground transmission lines that are used to deliver electricity to the customer. The smart grid network that is the focus of this thesis imagines a completely different future and the review of related work below focuses on five topics (site suitability; wireless communications tower visibility; area coverage; solar panel obstruction from trees; and communications tower site suitability in a smart grid network) and past works that overlap with the work at hand.

2.1 Site Suitability

Energy asset location-allocation or site suitability methodologies are not a new idea. Decision analysis incorporating multiple criteria and rooted in GIS site suitability evaluation has been deployed for several decades and has been used in determining optimal location proposals for power plants, wind turbines, solar farms, and smart grid communication towers. The criteria evaluated distinguish one site suitability study from the next. Carr and Zwick (2007) point out that site suitability modeling dates back to Charles Eliot and Warren Manning in the 1890s, who would place transparent sheets onto windows and analyze multiple site traits concurrently. They would then deem some locations as more suitable based on the results of their analysis. Manning (1896) later developed natural resource overlay maps that contributed to classifications schemes for the U.S. government. In the mid-1900s, English and Scottish town planners would overlay maps, eliminate unwanted areas, and combine the results into a kind of site suitability analysis. This process was transferred to and popularized in the U.S. through Ian McHarg's book "Design with Nature," (McHarg 1969) which described the process of overlaying vector data in mapping processes. By the 1960s, site suitability analysis using a nested hierarchy technique was deployed by Alexander and Manheim (1962) in transportation models within the U.S. A nested hierarchy approach to site suitability incorporates two or more hierarchical levels within the project data in which lower variables constitute a group that is contained by the parent data. In the 1980s map algebra was applied to cartographic products, which facilitated computations using multiple map layers (Arafat, Patten, and Zwick 2010) and by the 1990s GIS as a widespread product further proliferated the use of site suitability analysis in decision-making processes.

2.2 Wireless Communications Tower Visibility

Deane, Rakes, and Rees (2009) proposed a methodology for creating a cellular wireless network that provides coverage to all customers within a region while accounting for varying terrain and line-of-sight. He used a mathematical model to meet the needs of last mile service, or ensuring that all customers in dense areas were within one mile of a tower. The study proposed a grid of rectangular cells overlain on the service area, with a center point representing a potential tower site. Treating each potential tower in the model as a row and each potential customer as a column, line-of-sight was then determined, a value of one was given to represent coverage and a zero was given for non-coverage. The procedure did not, however, attempt to provide coverage to all customers but only as many as were necessary to justify tower expenditure. A hierarchy was implemented in which customers of greater financial value were given a higher priority. Tower placement was primarily determined by coverage such that it fell within budgetary constraints, with coverage being line-of-sight determined by both terrain and antenna range. One small change in Deane, Rakes, and Rees's (2009) mathematical model, or heuristic algorithm, allowed for the possibility of providing coverage to all customers. The model traded a portion of completeness or accuracy as a compromise for efficiency in an earlier model created by Scheibe et al (2006). Deane, Rakes, and Rees's (2009) study incorporated visibility analysis along with financial considerations and as a result recognized some tower locations as having a greater ability to see customers than other locations and noted that some sites on top of hills had a full radius of visibility when compared to others that did not. Each tower was associated with a list of customers that it had visibility to. This thesis drew upon Deane, Rakes, and Rees's (2009) work in that a visibility analysis was combined with socioeconomic factors to determine where an ideal placement for each communications tower in a network would be. A square grid containing a center point was used as a basis for grid creation in this thesis project as well as in Deane, Rakes, and Rees's analysis. Customer locations were given a zero value for non-visibility and a one value for visibility according to the ArcGIS visibility analysis results. Each tower placement is sufficient to ensure that all customers are within one mile of an asset.

2.3 Area Coverage

Church and Revelle (1974) were the first to coin the term Maximal Covering Location Problem (MCLP) for siting facilities that maximize demand area coverage. The concept has been applied to various services, such as emergency vehicle housing, sirens, and bus stops. The goal is to provide coverage to a region using the lowest number of facilities possible while leaving no area without service. MCLP is the precursor to a smart grid network in that it incorporates varying geographic factors into individual asset output range.

Adenso-Diaz and Rodriguez (1996) introduced a methodology for placing ambulance bases in Spain so that all residents within a region could be reached based on specified maximum response time. The study used an MCLP process to maximize output while minimizing the number of sites used in the study by deploying Church and Revelle's (1974) mathematical approach. Ambulance bases must adhere to maximum time of response standard as a result of emergency assistance procedures in which customers have little time to spare in life emergency scenarios. The minimum standard time used in the Adenso-Diaz and Rodriguez (1996) study was 15 minutes, and ultimately it was concluded that 67 bases were needed in order to meet this criterion for each station and 40 bases were needed in order to reach the entire population within 25 minutes. This thesis project shared several similarities with Adenso-Diaz and Rodriguez's (1996) study in that varied terrain had the greatest impact on network site location performance. In Adenso-Diaz and Rodriguez's (1996) study, the northern region near the Cantabrian Mountain Range was very mountainous with slow and difficult roads connecting residents to small villages. The southern region was more urban with straight roads and more rapid access. For this reason, sites had to be placed closer together in the north and could be spread out more in the south. In this thesis project, sites would also need to be closer in proximity in mountainous regions because propagation of signals would be negatively impacted by the rugged terrain.

One of the most directly related analyses to this thesis project is Murray and Tong's (2007) suitability siting for warning sirens, such that the city of Dublin, OH receives coverage from a specified number of sirens. The company's goal, however, was to minimize the initial outlay by deploying as few sirens as possible in order to ensure that all residents are within sound range of at least one asset. Murray and Tong (2007) deployed the concept of continuous space in choosing optimal site placement, which allows for siren placement at any geographic location so that it contributes to serving as many residents as possible. Each resident must be within sound transmission range of at least one siren. Murray and Tong's (2007) study also contained assets which were omnidirectional, propagating in straight lines in all directions. The study was unique in comparison to its predecessors in that it contained ArcGIS points, lines, and polygons as opposed to only point features. Similar to Deane, Rakes, and Rees's (2009) work, a mathematical model was established in order to determine locations that maximize total coverage and showed that some locations were more suitable in providing coverage than others. Areas of overlapping coverage were determined to achieve greater efficiencies in site placement than areas of single coverage. Therefore, multiple areas determined to be of high importance could be covered by a single location when these optimal locations were used. This thesis project drew upon several concepts in Murray and Tong's (2007) work. The idea that some locations provide coverage to greater numbers of customers was a theme in this thesis as well as Murray and Tong's (2007) work. The overall goal in this thesis was also to minimize the number of assets used while providing coverage to all residents. Communications towers in this thesis project were also omnidirectional and assumed to propagate straight lines in all directions, but the assumed signal output limit was set at one mile as opposed to 976 m in Murray and Tong's (2007) work. The overall goal in either scenario is to minimize the number of assets used in providing coverage to a region. Murray and Tong's (2007) siren network coverage of demand regions is demonstrated in Figure 4.

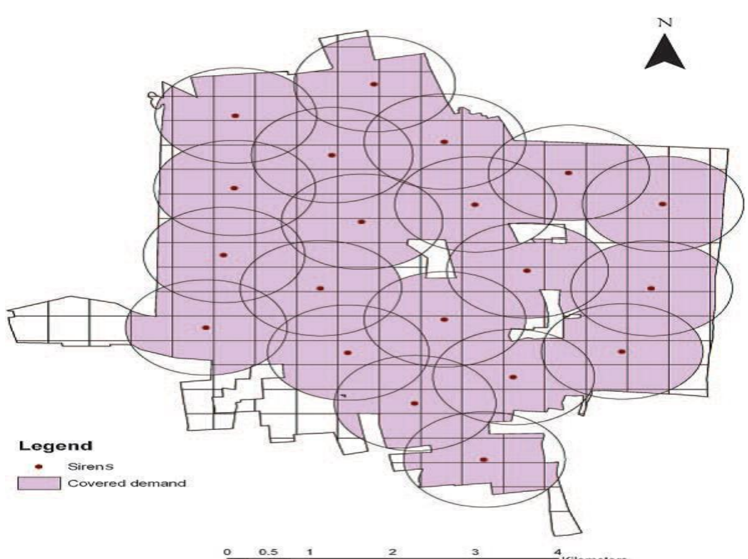


Figure 4: Murray and Tong's (2007) siren network coverage of demand regions in Dublin, OH

Murray et al. (2008) proposed a methodology for achieving MCLP using a Voronoi diagram and choosing an optimal location along the medial axis, or set of all points having more than a single point on the Voronoi diagram object boundary. Voronoi diagrams are applicable to smart grid network development in that flat areas represent larger diagram regions, while steep terrain represents smaller regions. In emergency vehicle siting, dense urban areas with slow travel times would increase the need for facilities closer together, while major highways and fast travel times, such as occurs in rural regions, would allow for greater distance between facilities. In smart grid network deployment terrain, meter density and available public roads determine distance between assets, resulting in a network resembling a Voronoi diagram in that each cell represents the communications tower range for a specific set of the conditions.

2.4 Solar Panel Obstruction from Trees

This thesis project will also include proximity to dense tree cover in an attempt to incorporate a solar radiation variable into the analysis results by using tree canopy/density data similar to Olivier (2009), who deployed GIS-based site suitability analysis incorporating distance to dense tree cover that would potentially obstruct solar panels as well as distance to utility lines and market value in a five-point scoring system. Weights were assigned to each variable—distance to power lines was assigned a weight of 40 percent, parcel market value was also assigned a weight of 40 percent, and parcel tree cover was assigned a weight of 20 percent. Features with a score of five were exported into a new dataset representing the optimal site suitability locations. This thesis project drew on Olivier's (2009) work in that tree canopy was categorized, then subsequently included in the analysis alongside distance to power lines and the nearest public road. Tree obstruction values as they relate to solar panel coverage in this thesis project were further grouped into light, medium, and heavy density classes.

2.5 Communications Tower Site Suitability in a Smart Grid Network

Benham (2012) used elevation, distance from existing towers, distance to Advanced Metering Initiative (AMI) meters, and a slope of greater than 15 degrees in determining optimal site placement for communication towers in a smart grid. Benham (2012) answered the question of whether the meters were able to communicate with the tower, but did not address site acquisition issues related to tower placement. However, Benham's (2012) work does highlight the need for communication tower placement that is approximately evenly spaced, uses the fewest towers necessary to cover a geographic region, and maintains a line-of-sight with all meters. Benham (2012) classified meters and communications tower buffers into six separate classes with break points at intervals ranging from one mile up to six miles. The study weighed three factors related to visibility— elevation, meter distance to communications tower, and tower distance. Elevation was given the strongest influence on visibility with about half of the overall weight. The study assumed that all meters within five miles of each communications tower were covered if they also maintained visibility with a tower. The study also used a "Buddy mode" in which one meter without coverage can relay a message to a neighboring meter that does have coverage and the signal from the former will be read at a tower.

This thesis project drew on Benham's (2012) work in that each meter was given an attribute identifying the nearest communications tower, so that it is possible to view which meters each DCU is responsible for providing coverage to. This thesis also used this knowledge to associate visibility values with eight surrounding DCUs, as meters could be visible to neighboring communications towers even if they are not visible to the nearest communications tower. Benham's (2012) work is also applicable to the meters visibility portion of this project in that it attempts to provide coverage to all meters within a region using the fewest communications towers possible, based on MCLP fundamentals. There are a number of potential geographic scenarios in which this concept would be necessary, including covering a region with emergency response facilities, implementing park ranger territories to cover an entire forest, constructing health facilities to provide service to a region, constructing irrigation systems to cover an entire agricultural territory, or deploying cell towers to meet the needs of a city.

Chapter 3: Methodology and Data Sources

The purpose of this thesis project was to capture the relationship between potential DCUs and the surrounding meters while accounting for factors that could prevent communication or tower construction. The data included building shapes and sizes to identify possible meter locations and road centerlines to determine possible DCU locations within public rights-of-way. A grid of evenly spaced points representing each DCU was created and each feature was relocated to the edge of the nearest street and evaluated for intersection with dense tree cover and high voltage power lines. An analysis was then carried out in which each meter was associated with the nearest DCU and a distance calculated from the former to the latter. Next, a yes/no line-of-sight value was calculated for each meter in relation to the nearest eight DCUs, or half of the entire network. A relationship was ultimately established between each meter and DCU based on proximity and visibility. Meter visibility to each DCU was calculated, with meters lacking visibility to any DCU visually displayed so that a communications tower could be added to the vicinity.

3.1: Data Sources

3.1.1 Address/Housing Data

Housing locations for this project were obtained as building footprint data from the City of San Luis Obispo fire department which digitized an extract from OpenStreetMap with 2011 aerial imagery varying from six-inch to one foot resolution throughout the city (Figure 5). Each polygon feature represents the approximate footprint of a building. Building footprint data are a valuable asset in identifying approximate utility meter locations, as meters in the real-world are normally located along the walls of homes and businesses. Address points were obtained from San Luis Obispo County and clipped to the City of San Luis Obispo for the work at hand.

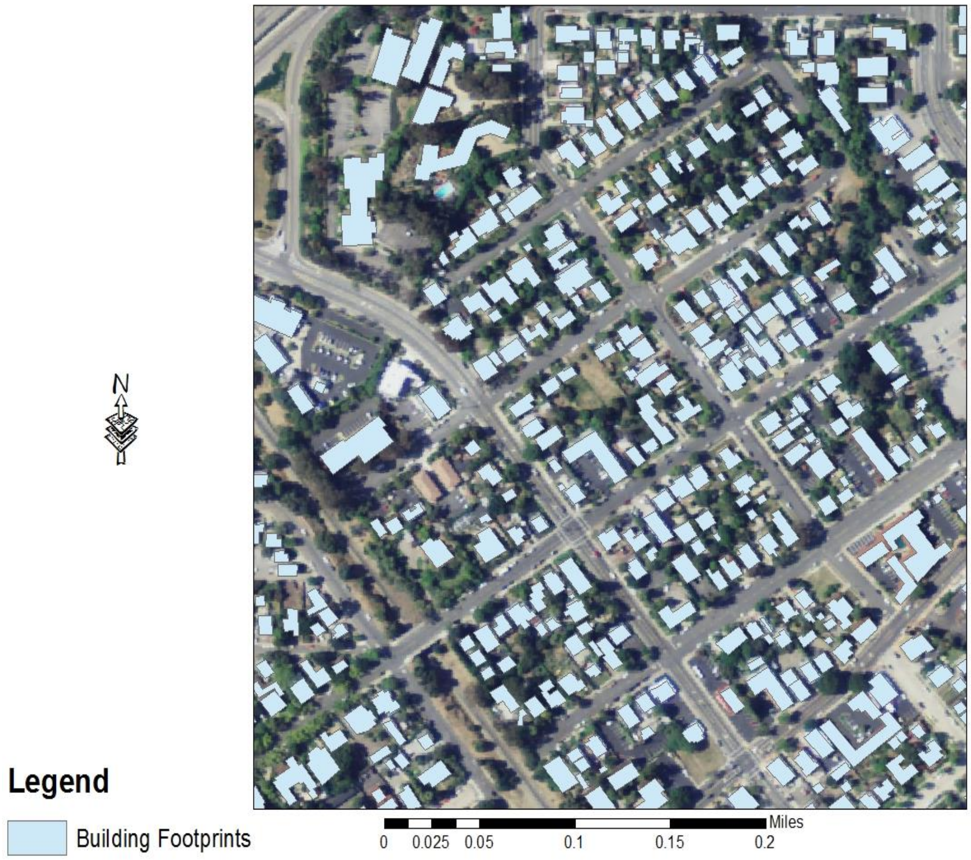


Figure 5: Map showing part of the San Luis Obispo building footprint data layer

3.1.2 National Elevation Dataset

The National Elevation Dataset (NED), a raster file representing topographic heights, was downloaded from the U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service's (NRCS) Geospatial Data Gateway website and used with Esri's Viewshed tool to identify the locations which were visible from a given point by running a comparison between the heights of a pair of cells. The relative success of the viewshed calculations is directly dependent on the NED's accuracy. Ten meter, or one-third-arc-second, resolution data cover most of the U.S., and are surpassed by three meter resolution, data in limited areas. The latter resolution or even finer resolution data acquired from specially flown LiDAR data acquisition programs may be appropriate for smart grid deployments throughout regions in which a company wishes to purchase better quality data products. The 10 m NED data used for this thesis project (Figure 6) was produced by the USDA-NRCS's National Cartography and Geospatial Center as multiple raster quadrangle Geotiff images in a seamless mosaic.

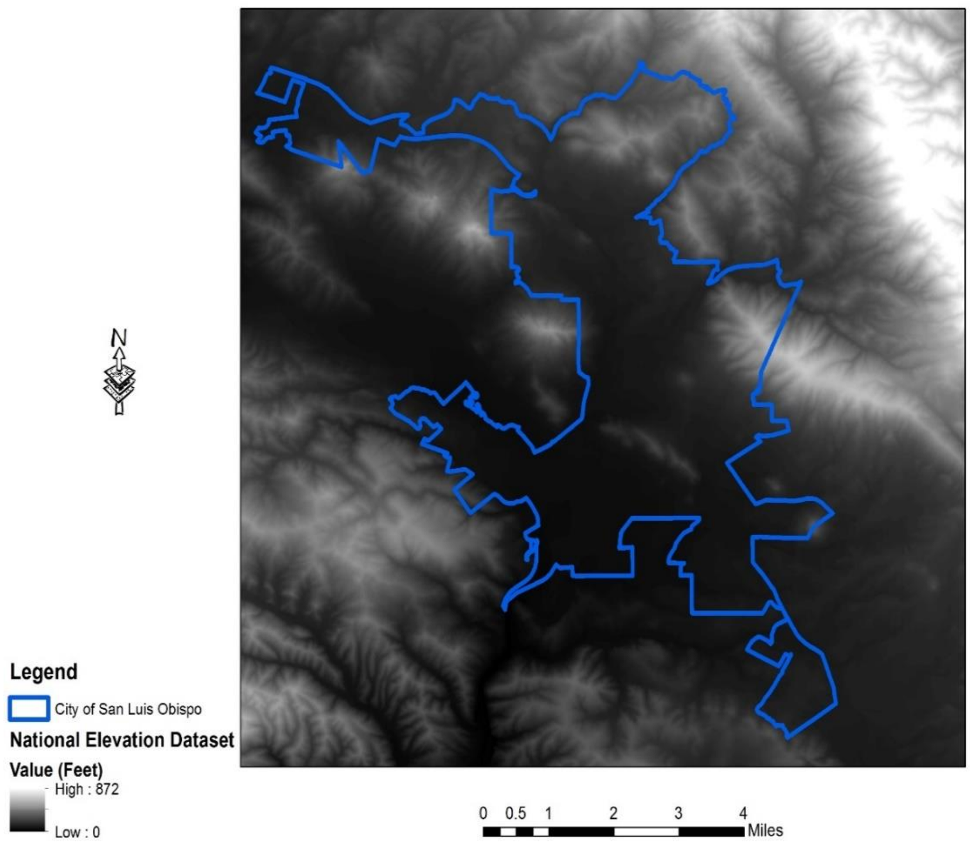


Figure 6: Map showing City of San Luis Obispo boundary superimposed on National Elevation Dataset

3.1.3 Road Centerlines

The placement of a communications tower may not be economically feasible on private roads throughout southern California. The acquisition of an easement is not necessary on public-maintained roads, minimizing temporal and economic constraints associated with the construction of a DCU on public streets. The most important factor in determining appropriate roads data for this project was the ability to distinguish public and private roads. The San Luis Obispo County roads polyline shapefile created by Contact One and made available on the County website fulfilled this project need, because it included a “Maintained By” field, which specifies the maintenance entity for each road feature. This particular roads dataset is optimal because maintenance entity values within this field can be grouped into public and non-public classes, thereby allowing the calculation of the distance to the nearest public right-of-way. For instance, non-public roads would include those maintained by private land owners, the Los Padres National Forest, and the Bureau of Land Management (BLM). San Luis Obispo County’s road data were created in 2010 by various GIS agencies within the county and ultimately quality control checked by Contact One. Road centerlines were based on a conglomeration of one foot and six inch resolution aerial imagery, meaning that each pixel records the standard reflected color of an area that is six inches by six inches (Focal Flight, 2012). Six inch aerial photography is normally produced on a custom basis (as was done in this instance by Focal Flight). San Luis Obispo County’s road centerlines data are most likely as good as any streets data in the US; however, all heads-up digitization of roads data possesses inaccuracies in specific areas and these errors may have an effect on the results of the distance to public-maintained road calculations. The work performed to convert the street centerlines to polygon features is described later in Section 3.2.2.

3.1.4 Powerlines

Transmission or power line data was obtained from the U.S. Geological Survey’s (USGS’s) GIS Data website and covered the western half of the U.S. The dataset originated in 2004 and is provided in a vector polyline format. The data depict primarily high voltage and long distance power lines, but also some low voltage and smaller power lines. The data are not comprehensive because they do not represent all of the power lines that exist on the ground, but they are the best available with the possible exception of the data maintained by the energy providers operating in specific regions.

3.1.5 Vegetation Cover

Smart grid communications towers operate with a solar panel unit installed on the pole as a power source. Proximity to dense trees might obstruct sunlight from reaching the units. Tree density data for this thesis project were captured from aerial imagery using a "heads-up" digitizing technique to create a polygon feature class. The data were then classified into one of three groups— heavy, medium, and light tree density— based on visual canopy assessment for subsequent inclusion in the site suitability assessment tool developed in this thesis project.

3.2: Building the Smart Grid Network

The focus of this project was to devise a complete system for designing a smart grid network that covers a small city. Upon tool deployment, each utility meter would contain attributes representing the name as well as the distance to the nearest communications tower, a numeric value representing whether the DCU was visible or not, thereby allowing for the possibility to see how many as well as which towers each utility meter has line-of-sight with. A network was proposed by placing a communications tower at each intersection on a grid that covered the City of San Luis Obispo. Each communications tower was then snapped (i.e. assigned) to the nearest edge of public-maintained roads measuring 40 feet in width. Meters were then snapped to the edge of the appropriate building footprint throughout the city before calculating distance and viewshed variables between meters and communications towers. Surface obstruction analysis was then conducted by assigning tree cover to one of three classes— light, medium, and heavy density and intersecting this layer with the complete communications tower network. The final results demonstrate a communications network that could potentially be constructed in the real-world, that is likely to avoid obstructions, that maintains a series of clearly defined relationships with surrounding utility meters, and that possesses a collective line-of-sight to all utility meters with the potential to call out those meters for which there is no visibility to a single DCU.

3.2.1 Generating a Network Grid

Smart grid communications towers, according to Benham (2012), can receive propagation signals within one mile in urban regions, five miles in suburban regions, and 10 miles in rural regions. As a standard for a smart grid deployment in Des Moines, Iowa in 2001, Aclara recommended a distance of one mile between each communications tower in order to guarantee coverage to all meters within the metropolitan region (Des Moines Water Works, 2011). For this reason, a network was created by placing points on a square grid that measured one mile on a side. The grid was created using ArcGIS's Create Fishnet tool and the number of rows and columns was adjusted in order to cover the City of San Luis Obispo appropriately. Within ArcGIS's Create Fishnet tool, there is a checkbox to allow the creation of label points at the geographic center of each square grid cell. The result was a grid of points covering the City of San Luis Obispo at a one-mile spacing in the west-east and north-south directions (Figure 7).

3.2.2: Public-Maintained Roads

The communications towers in a smart grid network must be placed at or very near the curb and within a few feet of where the pavement ends on publicly-maintained roads. Public-maintained roads are preferred because Southern California Gas Company (SCGC) has a franchise agreement with individual cities throughout the region such that the latter receives a small portion of the revenue that the former generates from its customer base (Scott Loveless, SCGC,

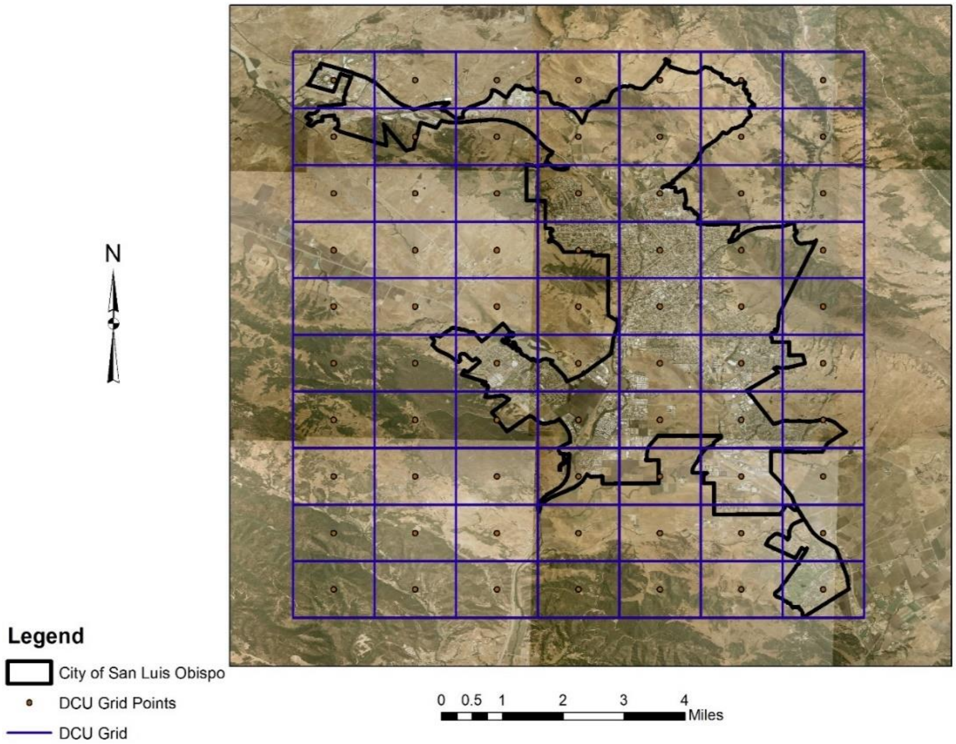


Figure 7: Map showing grid and grid center points created with ArcGIS's Create Fishnet tool

pers. comm. 2014). If the public utility were to pursue easements on privately owned land, there is potential for rejection; whereas a franchise agreement between the public utility and a city ensures the process of placing communications towers is less expensive, faster, and contains less potential for resistance. If this were not the case in a particular smart grid project, then private roads could be retained in the dataset and distance could be calculated to all roads.

The analysis procedures built into the project tool began with an ArcGIS Select by Attribute process in order to identify and exclude all of the roads that are not maintained by a public entity. An SQL-based selection was used in which all names which are not public entities were selected, including unnamed roads, driveways, private roads, and roads maintained by the California Department of Fish and Game, California Department of Parks and Recreation, or the military. The criteria were created in ArcGIS's Select by Attributes Query Builder tool as a new selection process in Modelbuilder. The Select by Attributes tool allows for an SQL-based query that selects attributes according to specific criteria evaluated in an ArcGIS dialog box. ArcGIS's Delete tool was then applied to the selected features to remove all but the publicly-maintained roads from the input dataset used for subsequent spatial analysis procedures.

San Luis Obispo roads, in reality, are not single lines but have a specific width that allows for proper traffic flow as well as parking. The traditional standard as well as accepted practice for improvements within residential subdivisions is 36 to 40 ft. (Marshall, 2012). A 40-ft width accommodates 10 to 12 ft. travel lanes and eight foot parking on both sides of the street. DCU placement would be at or within a few feet of the edge or curb of a street. Therefore, a 20-ft. buffer on each side of the street centerlines was used to identify these locations.

After a grid-based network of communications towers was created, a process was needed to align each asset with a viable location at the edge of a road. The smart grid network shown in Figure 6 was used with ArcGIS's Snap tool in order to move the geographic location of each point to the edge of the nearest edge of a 40-ft. wide public road. This tool selects the nearest edge of a road feature and moves as well as connects a communications tower to the road feature using an ArcGIS technique called "Snapping." A map of a smart grid network snapped to the nearest road is shown in Figure 8.

3.2.3: Locating Utility Meters

The utility meter data began as a single point location that represented each house in the City of San Luis Obispo. The address point data for San Luis Obispo County was first clipped to a boundary of the City of San Luis Obispo. Housing points were then connected to the nearest

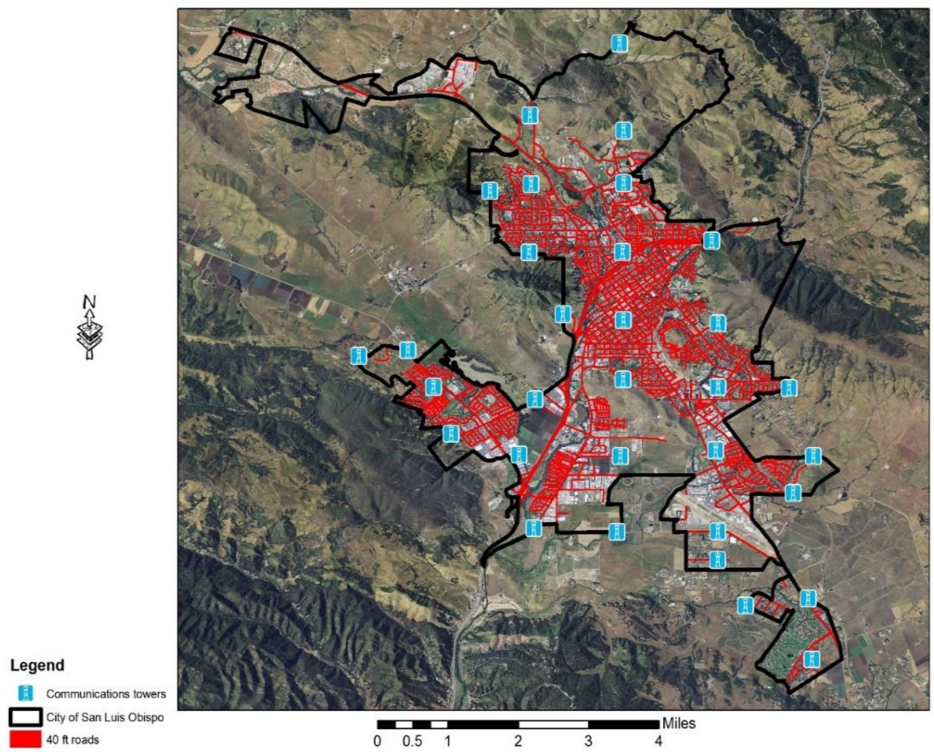


Figure 8: Map showing communications towers snapped to publicly maintained roads

edge of the closest building footprint feature using ArcGIS's Snap tool. This placed the utility meters near one of the walls of each house, closely replicating their locations in the real-world. Puget Sound Energy (2014) prefers gas meters to be located on the front wall of a house or within the front one-third of the side wall, for example. According to Puget Sound's analysis, utility meter locations are at times located on the driveway side of a home but also often on the front wall, which could also be the opposite side of the house from the driveway. When snapping housing points to building footprint data, the most likely result is meters placed in front or on the side of a house, since most address data places street address points at the street or near the front center of a residence. The results from snapping utility meters to the nearest edges of building footprints in the City of San Luis Obispo for this project is demonstrated in Figure 9.

Figure 9: Map showing utility meters snapped to the nearest edge of the building footprints in a part of the City of San Luis Obispo

3.2.4: Locating Power Lines

The proximity to the nearest power line(s) is an important determining factor in a site suitability analysis for a smart grid communications tower. Overhead power lines could potentially obstruct a vertical construction path, interfere with DCU performance, and/or create an electrical safety hazard. The utility company rights and safety standards relating to power lines within the scope of the Advanced Meters project are regulated by the California Public Utilities Commission

(CPUC) (Scott Loveless, SCGC Site Acquisition Manager, pers. comm. 2014). The CPUC mandates that attachments to powerline poles cannot exceed 20 ft. in height. This regulation rules out communications tower placement on a powerline pole as a DCU needs to be at least 25-ft high. According to Loveless, public utilities must also maintain a minimum distance of 10 feet from powerline poles for safety reasons and also to allow service personnel room to climb a pole in maintenance procedures. The need is clear— the communications tower must be located 10 ft or more from the nearest power line.

The power line data obtained for this project were first re-projected using ArcGIS's Project tool to a California State Plane coordinate system so that ArcGIS's Near tool results were represented in feet as opposed to meters. ArcGIS's Near tool was then deployed for each proposed tower location to determine the distance to the nearest powerline feature. A NEAR-DIST field was added to the proposed location feature class containing a measurement in feet to the nearest powerline. The resulting dataset was then transformed into a feature layer so that a symbology definition could be applied according to powerline proximity. Distance from zero to 10 ft were symbolized with a unique score of one to indicate locations that are unacceptable for DCU construction.

3.2.5: Potential for Communications Tower Obstructions

It is a challenge to measure distance to hardwood trees. Trees that do not obstruct radiation from reaching DCU solar panels could provide a benefit by blocking customers from seeing a communications tower. Therefore, it may be beneficial to place a DCU in areas with smaller numbers of moderate-sized trees that hide DCUs from customers but do not block sunlight from reaching the DCUs, themselves. For this reason, distance to trees was measured in regions with large numbers of large trees, such as oak. Tree density was captured by hand and classified as high, medium, and low density by digitizing forested areas from 2012 one-meter resolution aerial photographs. Each region was visually inspected and rated using color depth and level of resulting opaqueness. Low density attributes were assigned to areas that were lighter in tone or possessed greater perceived space between canopy areas. High density was assigned as an attribute to regions that were darker in tone and/or that gave the appearance of less space between trees. An obstruction map showing the potential of trees to block sunlight from the proposed DCU towers is reproduced in Figure 10.

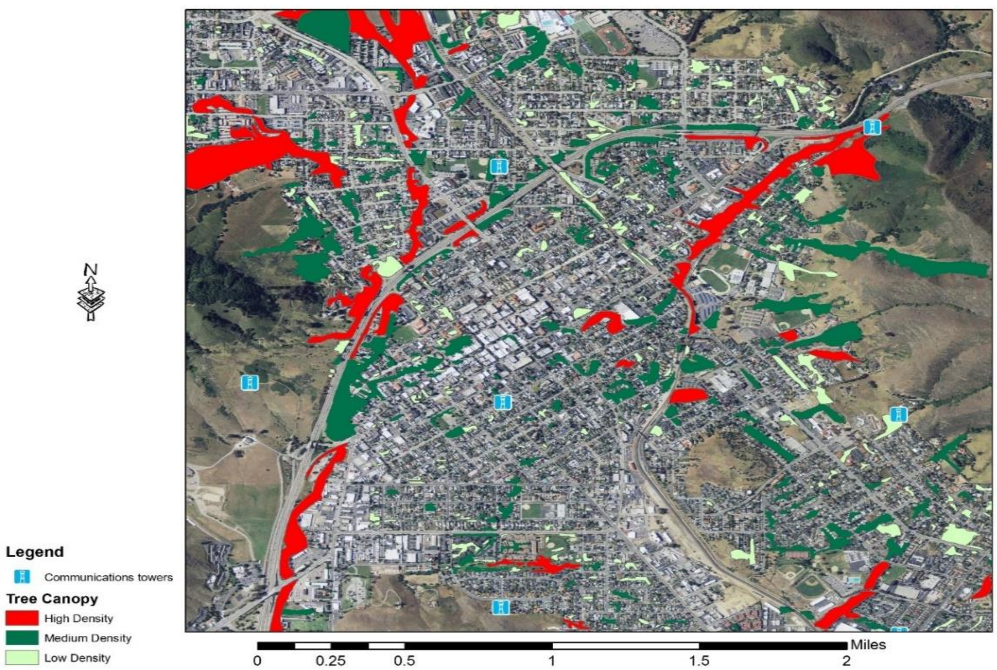


Figure 10: Map showing DCU tower tree obstruction potential

3.2.6 Utility Meter Association with and Distance to Nearest Communications Tower

Each communications tower within a network grid should optimally maintain a line-of-sight with all meters within a one-mile radius. Therefore, the visibility analysis procedures began with attributes for each utility explaining which DCU is the closest and how far away it is. If the previously mentioned Aclara (2014) specifications are adhered to in grid creation procedures, all utility meters should have a DCU that is less than 5,280 ft away. The allocation of utility meters to DCUs is demonstrated for a part of the City of San Luis Obispo in Figure 11. The map associates the nearest DCU to each meter and compares that association to a one mile radius surrounding each communications tower.

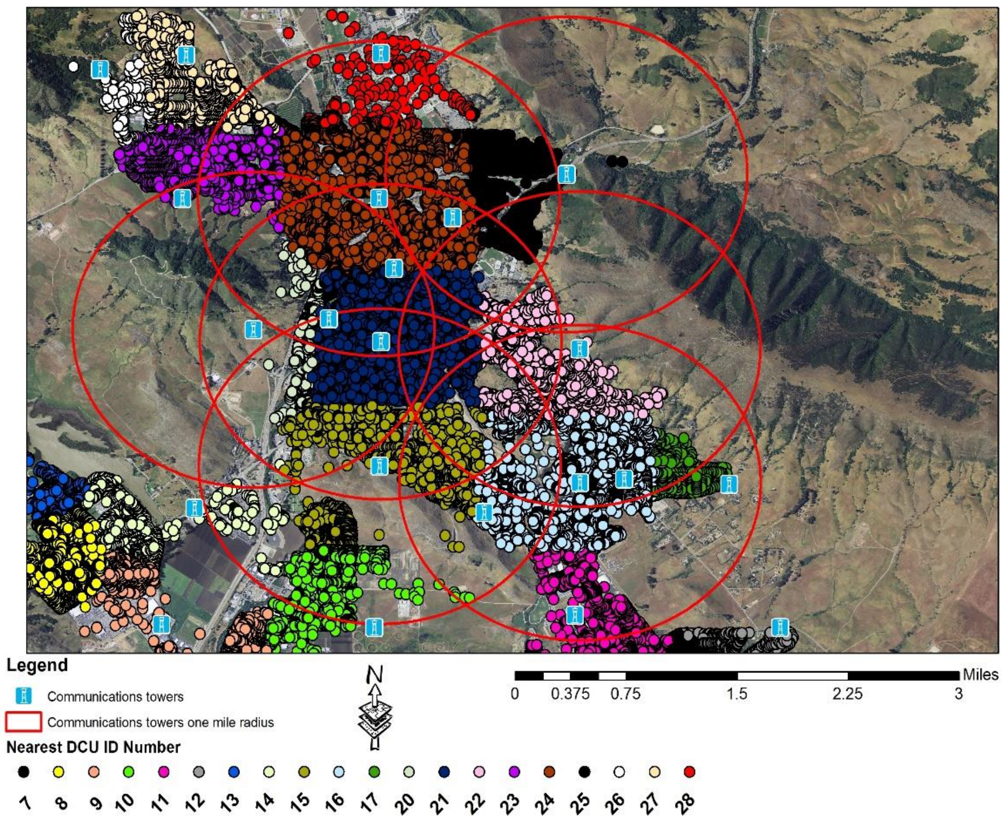


Figure 11: Map showing utility meters and nearest communications towers in a part of the City of San Luis Obispo

The distance to the nearest feature of interest was calculated in ArcGIS using the Near tool. ArcGIS's Near tool allows a user to specify a radius in which to measure a distance to the closest feature within a dataset of interest. In this case, each meter will gain an attribute describing which communications tower is closest in geographic proximity as well as the distance to that asset in feet. ArcGIS's Select Layer by Attributes tool was next used to check if each utility meter has a DCU within one mile. The tool operates on an SQL query that calls for a selection of all records that contain a value greater than 5,280 in the "NEAR_DIST" field. This operation separated these values from the remainder of the data, which were then run through the Make Feature Layer tool to initiate a data item to which symbology could be applied to identify which of the 32 communications towers throughout the city each meter was associated with (Figure 11). The number of meters associated with each DCU can then also be calculated and used in tandem with visibility analysis in determining which communications tower should have visibility with individual meters.

3.3 Meter to Communications Tower Visibility

3.3.1 Observation Points Tool

The most important factor in smart grid communications tower site suitability analysis is the visibility of the meters. All utility meters throughout a metropolitan region must be able to communicate with at least one tower in order to relay daily energy consumption patterns to the utility company, which will display results for consumer monitoring. Radio signals travel in straight lines when using lower frequency transmission signals, such as the 450-470 MHz range that southern California's Advanced Meters network is licensed to use through the Federal Communications Commission (Aclara 2014). Direct line of sight between source and destination are a fundamental requirement in meter-to-communication tower propagation.

ArcGIS provides a tool which calculates line of sight between two objects and can also incorporate the height of a tower as a variable in calculation procedures. The result is the equivalent of a yes/no response for each point-to-point analysis as to whether object A can see object B and vice versa. The tool calculates this visibility based on a raster file that contains elevation values for individual pixels. The tool returns a value of one for visibility between the two points or a value of zero for non-visibility. For this project, communication tower height was set to 25 ft, the most common and lowest standard deployed by SCGC for DCUs throughout southern California. Since this is the lowest tower height used for the Advanced Meters project, there is safety built into the analysis, as a greater height would only improve visibility to meters. Choosing a conservative denominator for tower height increases the likelihood that all meters will be correctly characterized in the real-world.

Site suitability began with the selection of a point in an ArcGIS shapefile that contained three important fields: a Feature Identification Code (FID), a NEAR_DIST numeric field that is capable of holding decimal values; and an OFFSETA numeric field set to 25 (ft). The NEAR_DIST field stores the distance calculation results from the proposed location point to a number of specific objects. An OFFSETA field is an ArcGIS standard for adding a specified height value to Observation Points tool results. If this field were not created, ArcGIS would use a one foot height for the source point, which in this case was a communication tower.

Propagation of the transmission of radio waves is directly linked with attenuation—which can be defined as the reduction in magnitude of a radio frequency signal from a transmitting station to a specified location along any transmission path (Michael 2012). ArcGIS's Observer Points tool is an important first step in calculating visibility to meters from a proposed communication tower location, but the 0/1 results may not tell the whole story. ArcGIS's Observer Points tool calculates a line of sight from one specific point taking into account elevation data, derived from the NED in this instance. Elevation data are important in calculating diffraction, or the interference of waves by any obstacle, in this case occurring when direct line-of-sight between the transmitter and the receiver is obstructed by an obstacle whose dimensions are considerably smaller than the signal wavelength (Qing 2005). The most significant obstruction to a radio frequency signal is a hill with an upward-facing slope, therefore elevation is important in calculating whether a meter can communicate with a tower or not. Since radio propagation may or may not pass through given objects, the line-of-sight provides an optimistic answer for this attribute. Any obstruction that can interfere with the visual line of sight can interfere with radio line of sight (Fleeman, Anderson, and Bird 2014).

The one-mile buffer calculated with ArcGIS's Observer Points tool was used as an input to clip the meters visibility analysis results, since the latter could expand several miles outward from the input feature of interest. Running ArcGIS's Observer Points tool on the proposed location produced a raster file that calculated a 1 or a 0 value (visible or non-visible) for each pixel within the source NED file. The resulting raster file was converted from raster to vector using ArcGIS's Raster to Polygon tool, with the resulting vector file receiving the 0 or 1 visibility value as a result of joining the raster and vector data. After the clipping procedure, the resulting vector file with visibility values was incorporated into the utility meters data via spatial intersect.

3.3.2 Utility Meter Visibility to Surrounding Communications Towers

Distance from utility meter to nearest communications tower as well as identification of meters within one mile are important steps in overall network analysis, but the heart of the analysis is in identifying the communications towers with which each utility meter has line-of-sight. For most utility meters, there is more than one communications tower within one mile (as was demonstrated in Figure 11); therefore, we needed to perform a yes-no visibility analysis with a portion of the entire network. However, the network was too large to incorporate all of the DCUs and utility meters into one analysis, so that the network was broken into four groups of eight communications towers and all of the utility meters within one mile of each tower were used for each part of this analysis.

ArcGIS's Observer Points tool was then run on each group in order to calculate whether each raster grid cell maintains visibility to a DCU. The tool assigned a value of one to cells that have visibility and zero to those without it. The power of the Observer Points tool is its ability to score visibility in relation to not just one but numerous feature points— in this case one or more surrounding communications towers. The resulting values, however, are in raster format and not compatible with the vector processing required for the remainder of the analysis procedures. The resulting raster file was run through ArcGIS's Raster to Polygon tool, which converts Observation Points tool results from a grid cell into a vector polygon. In the transition to a vector file, however, visibility values to individual DCUs are lost. After executing ArcGIS's Make Feature Layer tool on the vector polygon, the file is ready for joining the raster visibility values via ArcGIS's Add Join tool. A visibility or non-visibility value associated with each DCU was then added to the vector file which had lost one of its most important fields. The result of this operation was an attribute within each meter for visibility or non-visibility to each of the eight nearest DCUs. ArcGIS's Select by Attributes was then run on the aforementioned data using an SQL query that selects only those meters which had a zero value for all eight surrounding DCUs. This result singled out those meters that did not have visibility to any communications towers so that an additional communications tower could be placed in the vicinity to provide coverage. Executing ArcGIS's Copy Features tool exported out the selected features into a new layer of non-visible meters. The next chapter summarizes the methodology developed for this thesis project and describes the results associated with applying each of the aforementioned analysis processes in the City of San Luis Obispo.

Chapter 4: Results

This chapter describes how the work elements discussed in the previous chapter were linked with one another to provide a single end-to-end solution and the results of applying these processes depict how a smart grid infrastructure might be constructed for the City of San Luis Obispo. A network of communications towers was created in feasible locations for the City of San Luis Obispo and a relationship established between each tower and surrounding meters, based on proximity as well as visibility. The first goal for this thesis project was to place each DCU and meter in as realistic of a location as possible. The second goal was to avoid obstructions that would make DCU placement not feasible. The final goal with this smart grid network was to maintain visibility to as many meters as possible from a minimum of one communications tower. The following sections detail how this thesis project tool can accomplish the aforementioned goals.

4.1 Smart Grid Site Suitability Tool

4.1.1 ArcGIS Modelbuilder

ArcGIS Modelbuilder is an application in the ArcGIS environment used to build, modify, and manage models of ArcGIS processes. Inputs are fed into geographic processing tools and then output as resulting features. A workflow is the basis for modifying or analyzing data in order to accomplish specific tasks. Modelbuilder is also compatible with python scripting, which provides a condensed scripting language relative to other choices and is the most common platform that GIS applications are built on. Ultimately, Modelbuilder's greatest strength lies in its automation of processes that would normally require locating numerous tools in ArcGIS and running each individually. A final model is run in one step by the user and the results applied immediately to the data in ArcMap.

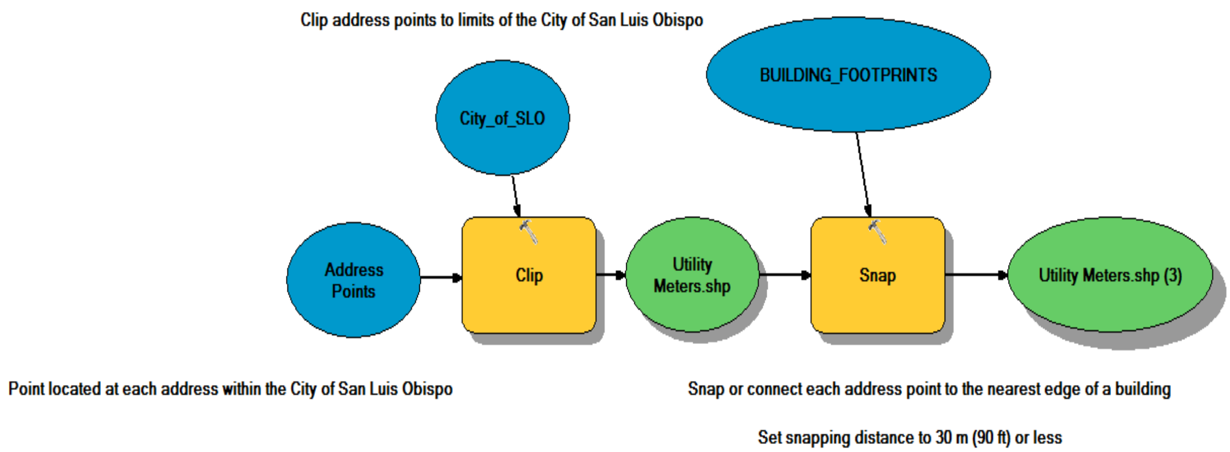
4.1.2 Tool Overview

The smart grid site suitability tool developed in this thesis project has the capability to accomplish numerous tasks necessary in developing a network that meets the MCLP standard of providing service to all residents in a region by using the lowest number of assets. The tool can be broken down into four process groups: feasible data location, network grid placement, proximity to obstacles, and network to meter analysis. The first two processes could be considered data preparation for a DCU site suitability analysis in that an attempt was made to locate features in as accurate of a geographic location as possible. The procedures ensure that each meter is snapped to the edge of the nearest house (Figure 12A) and that roads are 40 ft in width as opposed to a single line feature (Figure 12B). The next two processes create a network of communications towers where each tower is placed in as realistic of a location as possible but also likely to address the MCLP by providing coverage to as many houses as possible in the region. The MCLP issue is addressed by creating DCUs within one mile of each other (Figure 12C). DCUs are then snapped to the edge of the nearest publicly-maintained road as illustrated in Figure 12D.

The third group of processes in the tool run a communications tower proximity analysis in relation to power lines (Figure 12E) and tree canopy for safety and solar access reasons (Figure 12F).

The final pair of processes that make up the fourth and final group determine meter association with and distance to the nearest communications tower (Figure 12G) as well as visibility to the nearest eight DCUs (Figure 12H). A visibility or non-visibility value was then given to each meter as it relates to the eight closest DCUs by using ArcGIS's Observation Points tool. Meters with no visibility to any communications towers were finally singled out for placement of an additional DCU in the vicinity to provide coverage to all house meters in the area of interest (i.e. the City of San Luis Obispo in this instance) (Figure 12H).

A. Meters snapped to edge of nearest building footprint



B. Create 40-ft wide publicly-maintained roads

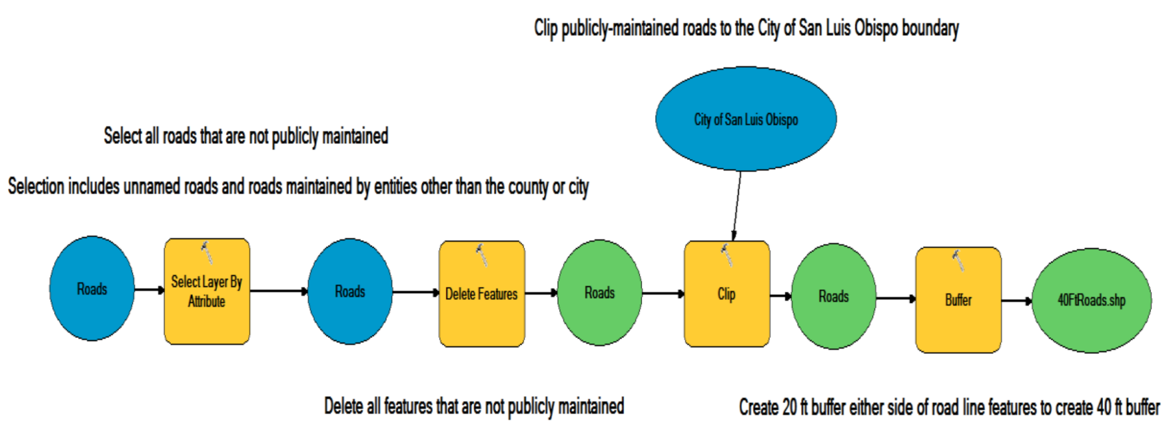


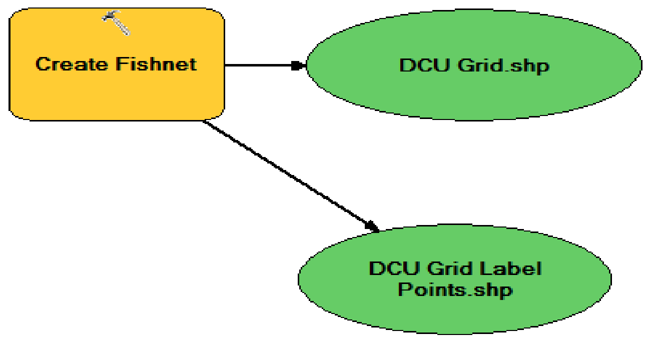
Figure 12 (continued next page)

C. Create network grid with one-mile spacing

Create grid that covers extent of City of San Luis Obispo

Specify sufficient rows and columns to cover city extent using one mile spacing

Clip grid to capture full extent of City of San Luis Obispo



Create point features at center of each grid cell

D. Network grid snapped to nearest publicly-maintained road

Connect or snap DCU grid locations to nearest edge of publicly-maintained road

Set snapping parameters for roads to feature edge and set distance to within one mile.

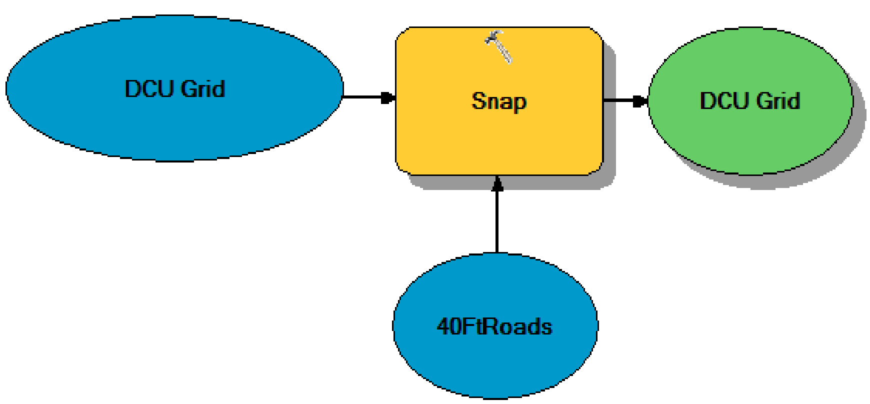
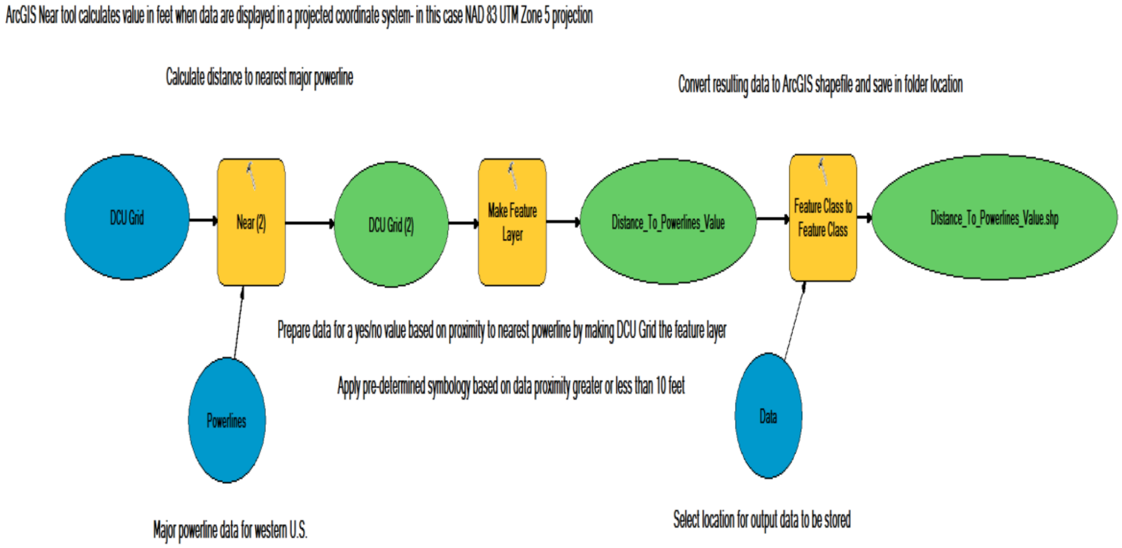


Figure 12 (continued next page)

E. Ensure distance of greater than 10 ft to high-voltage powerlines



F. Ensure DCUs do not intersect with tree canopy

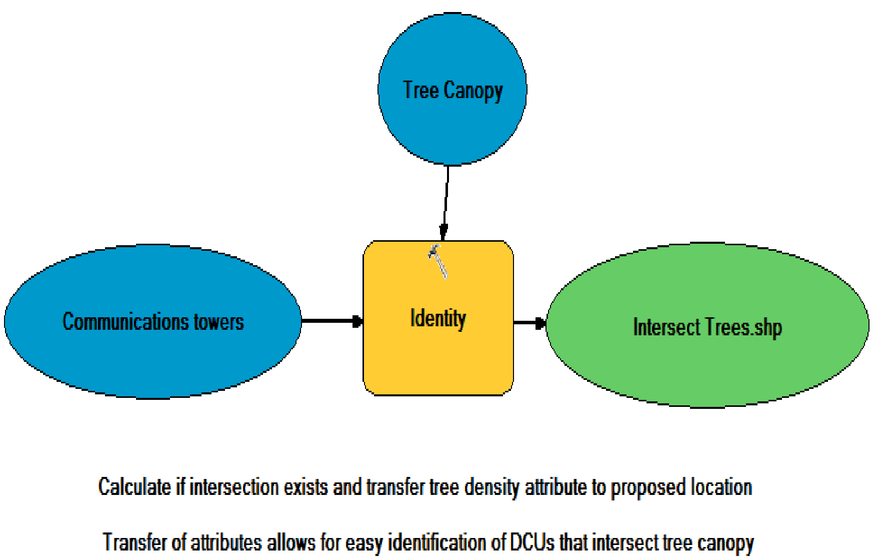


Figure 12 (continued next page)

G. Associate the nearest DCU with each utility meter

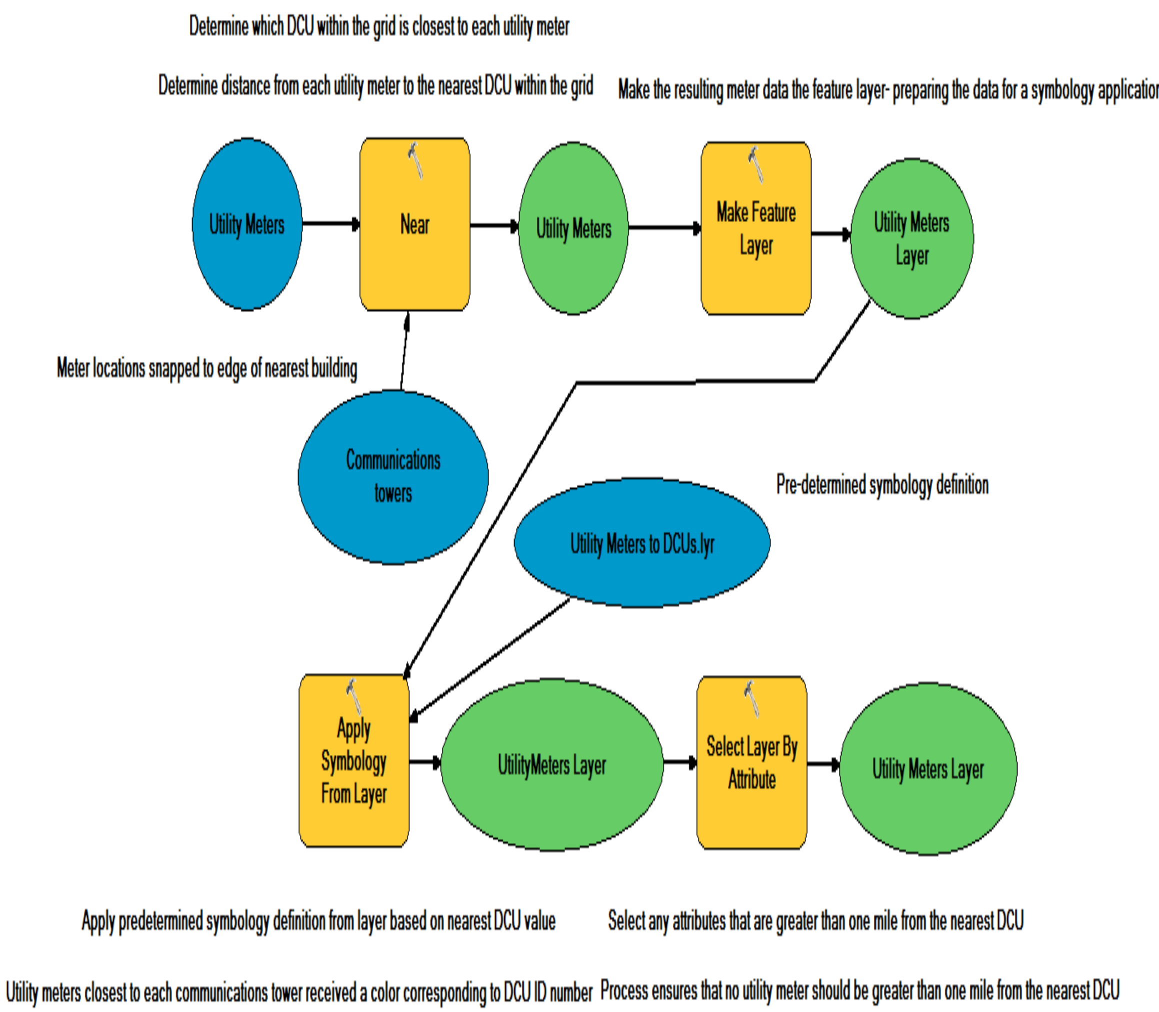


Figure 12 (continued next page)

H. Calculate a 0 or 1 visibility value for each meter to the nearest 8 DCUs and export new layer of meters with no visibility to any DCUs

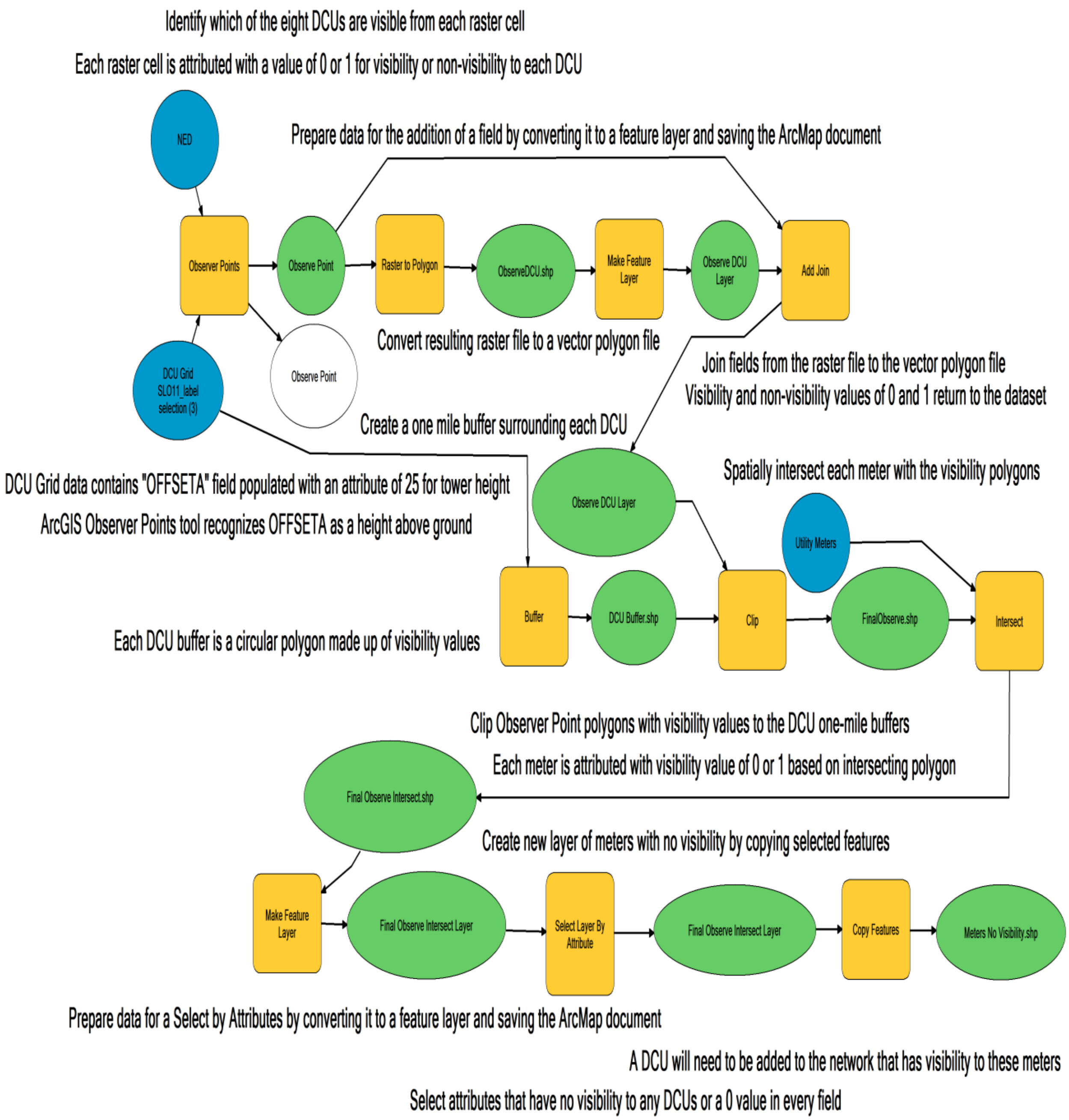


Figure 12: Smart grid site suitability tool in Modelbuilder

4.2 City of San Luis Obispo Application Results

4.2.1 Feasible Data Location, Network Grid Placement and Proximity to Obstacles

In applying the tool created in this thesis project, a network was created in which each communications tower was spaced close to one mile apart, depending on how far the feature was shifted in order to achieve placement on the nearest public-maintained road. The tool was successful in locating meters along an edge of each building footprint and in creating roads that were 40 ft in width.

The resulting grid created from the processes detailed in Chapter 3 placed 32 communications towers that were located approximately one mile from one another and cover the entire city. Meter-to-communications tower results were used at a later step to determine if there were regions that would need less spacing between DCUs, but the model developed and used for this application did not contain any logic for reducing distance between towers when relief increased.

Obstacles to DCU construction were successfully avoided in the process of snapping each asset to the nearest publicly-maintained road. Distances to powerlines were not less than 10 ft and ranged in value from 27.3 to 872.9 ft. Resulting points from the distance to nearest powerlines portion of the tool would have been assigned a red color for values of less than 10 ft, but this result was not encountered in the City of San Luis Obispo. Tool results for an intersection between the network of communications towers and tree canopy resulted in no points receiving the attributes of the tree canopy data. Since the latter data were grouped into high, medium and low density values a decision could be made if a low density area was acceptable for DCU placement upon aerial photo inspection. ArcGIS's Identity tool allows for a transfer of attributes from the tree canopy data to the DCU data provided that an intersection occurs. The results for proximity to obstacles demonstrated that all proposed communications tower in the City of San Luis Obispo network are likely to be a safe distance from powerlines and dense tree canopy areas.

4.2.2 Network to Meter Analysis

Results for the first part of the network to meter analysis— associating the nearest DCU with each utility meter— created an association between each meter and the DCU that was closest to it in terms of distance. The meter then gained a new attribute consisting of this DCU identification number. This result was included to cover the case in which the meter is not covered by any communications towers and to determine the DCU that was supposed to provide coverage.

The second field that the tool analysis created is a distance from each meter to the closest associated DCU. If this distance was greater than a mile, those meters would be selected by the tool to be singled out as an issue. A color was also given to each meter based on which DCU is closest in distance. This procedure delineated which groups of meters each DCU is primarily responsible to provide coverage to. The nearest DCU analysis additionally adhered to MCLP standards of breaking an overall region into smaller component parts that each feature is responsible for, similar to the idea of Voronoi diagrams deployed in past work of this type. Distance value results for all meters were all less than one mile, therefore no meters were selected by the tool. The meter distances to the nearest DCU ranged from 23.8 to 3795.9 ft, as shown in Table 1.

Table 1: Maximum distances from meters to nearest DCUs

DCU ID Number	Number of meters associated with each DCU	Maximum distance to any meter associated with DCU (ft)
0	70	2,280.9
1	345	3,311.0
2	55	2,418.1
3	193	2,474.1
4	339	3,695.4
5	34	3,622.8
6	458	3,303.2
7	556	3,136.5
8	1,514	2,926.5
9	902	3,660.2
10	1,178	3,671.4
11	1,182	3,388.1
12	183	2,888.8
13	1,123	3,134.1
14	479	3,227.0
15	2,108	3,557.1
16	2,774	3,465.4
17	245	2,732.8
18	27	1,623.4
19	87	2,150.8
20	417	3,202.4
21	4,537	3,585.7
22	988	3,489.5
23	1,626	3,669.2
24	4,923	3,674.3
25	680	3,364.2
26	124	2,489.3
27	924	3,687.0
28	570	3,336.4
29	1	1,718.8
30	2	3,625.4
31	3	3,795.9

Meter visibility from each 25-ft high communications tower was determined from each meter to a group of eight DCUs in the vicinity. The result was a field for each of the eight communications towers added to utility meters with the associated DCU number as the field heading. Each of the added fields contained a value of 0 or 1. Of the 28,647 total meters in the City of San Luis Obispo, 5.8 percent of the meters were not covered by any DCUs, 8.4 percent were covered by just one DCU, 8.4 percent were covered by two DCUs and 21.7 percent were covered by three DCUs (Table 2). The remaining 55.6 percent of the meters had visibility to more than three DCUs, leaving 1,660 meters without visibility to any DCUs as the primary issue in providing coverage to the region.

Table 2: Overall numbers of meters with specified numbers of visible DCUs

DCU Groups	**Number of Visible DCUs**						
	0	**1**	**2**	**3**	**4**	**5**	**≥6**
Group 1	31	338	267	420	330	458	455
Group 2	202	551	908	2,639	2,066	1,040	403
Group 3	1,358	1,283	800	2,462	1,885	2,604	1,676
Group 4	69	229	425	686	554	1,108	3,400
Total	1,660	2,401	2,400	6,207	4,835	5,210	5,934
Percent of Total	5.8	8.4	8.4	21.7	16.7	18.2	20.7

Five communications towers were added to the network in an effort to cover these meters— three in the northwest region of the city and two in the southwest region— as shown in Figure 13. These new DCUs reduced the number of meters without visibility to any DCU in half, lowering the number from 1,660 noted previously to 742, or 2.6 percent of the network. The meters without coverage after the addition of the five new DCUs are shown in Figure 14 and more than likely represent locations that represent special topographic settings (i.e. limitations) that impact visibility from DCU to meter.

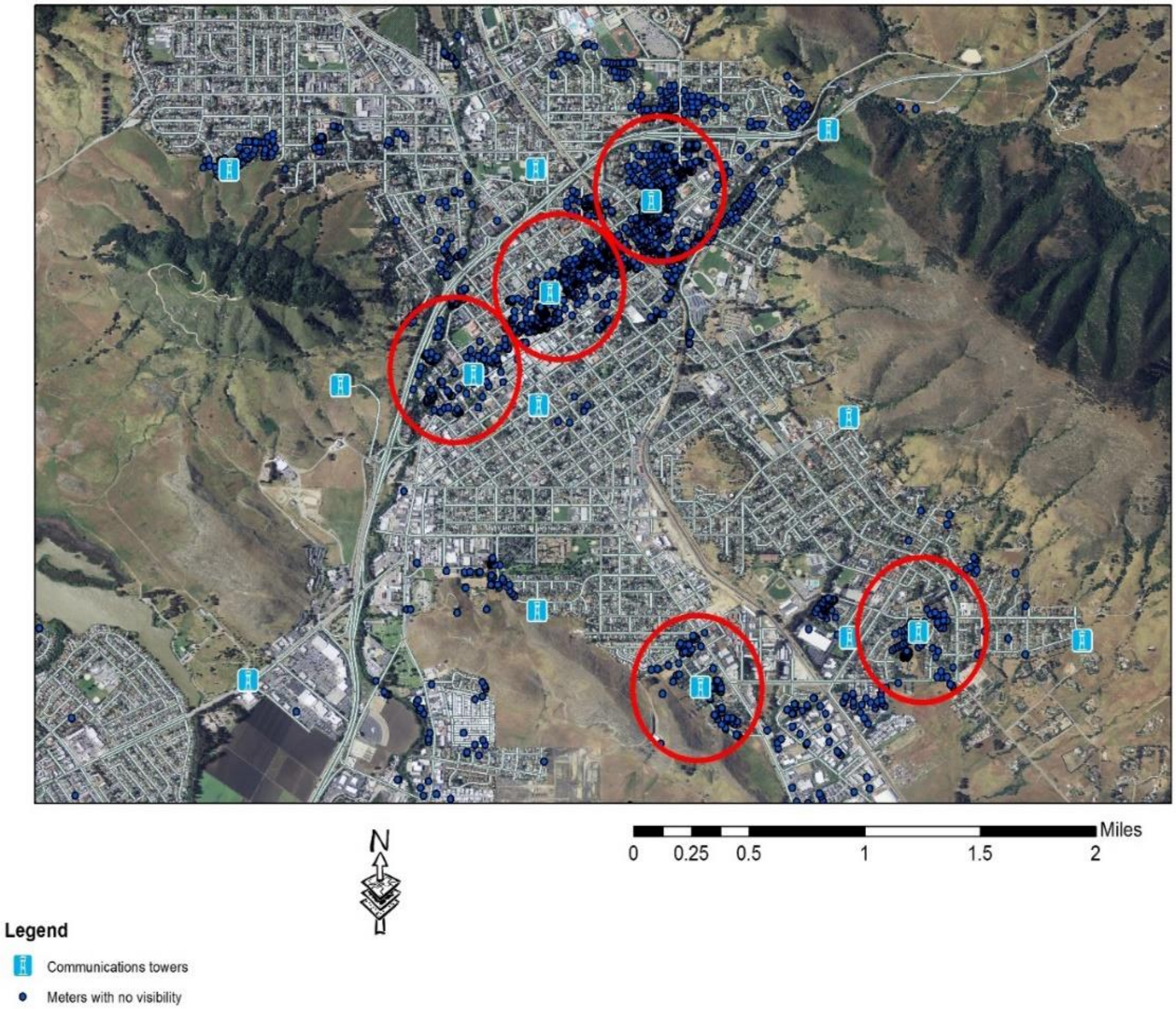


Figure 13: Locations of five communications towers added to the network to provide coverage to meters with no visibility

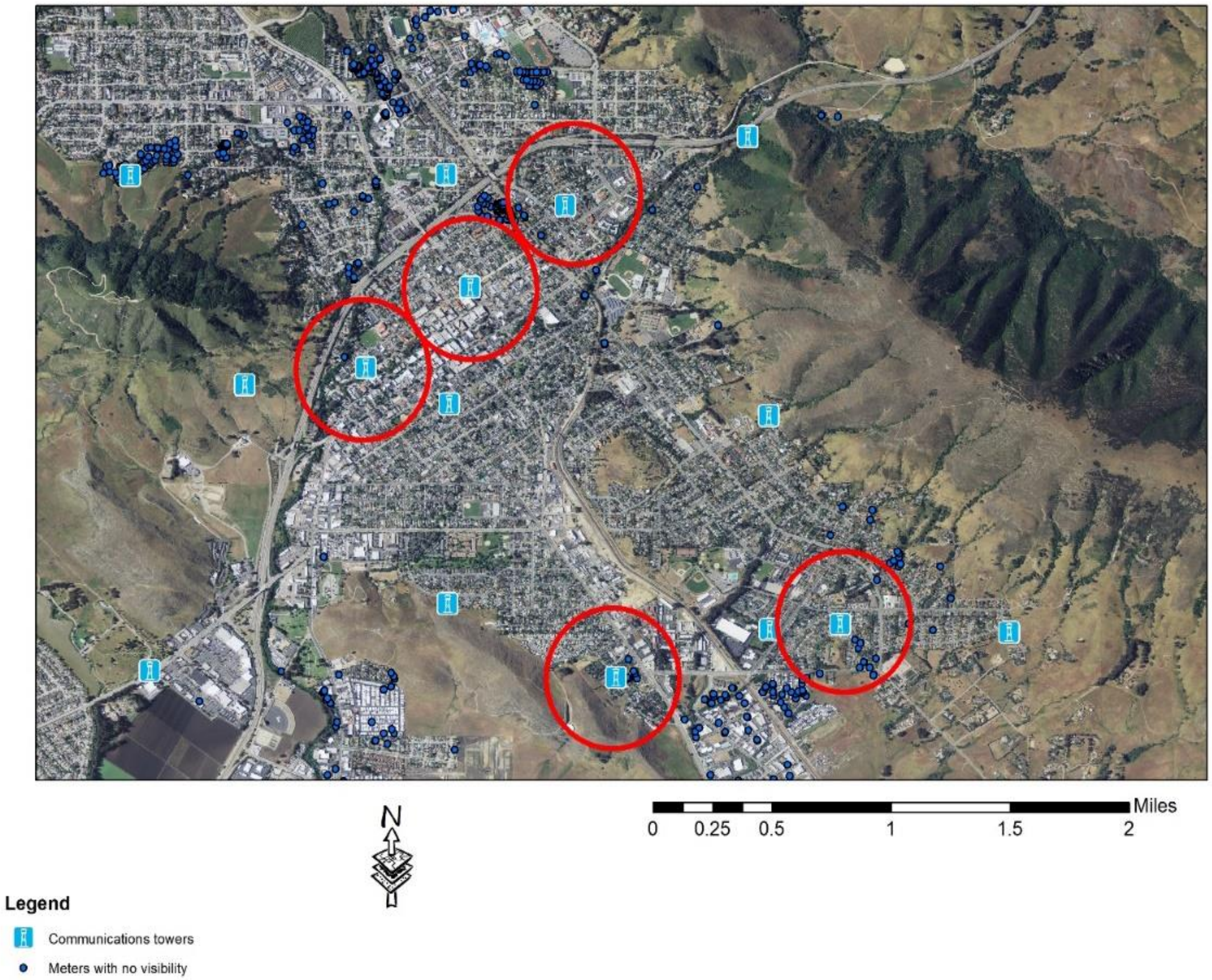


Figure 14: Locations of meters without DCU coverage after the five new DCUs were added to the network

Chapter 5: Discussion and Conclusions

5.1: Building a Smart Grid Network for the City of San Luis Obispo

As a result of this project's analysis procedures, utility meters within the City of San Luis Obispo were placed at the front or front side of a residence using building Footprint data as a base for geographic reference. In reality, utility meters could be located near the front corner or the front door of a house, on either side of the house near the front, or sometimes in basements or other nonstandard locations (Puget Sound Energy 2014). For this reason, snapping to the building footprint from an original location in the front street was the closest approximation possible. A network grid with one mile spacing between proposed points was also created and then connected to the nearest public-maintained roads with a 40-ft buffer to ensure placement specifically at or near curbside. An analysis was carried out which successfully identified the nearest communications tower to each individual utility meter as well as the associated distance to that asset. These values for closest DCU were symbolized using unique colors and displayed geographically for reference and further analysis (see Figure 11 and Table 1 for additional details). A meter visibility analysis was then completed in which each utility meter gained new attributes with values of one or zero representing visible or non-visible DCUs for each of the eight DCUs within one of the four groups that spanned the entire city. From this analysis, it was possible to associate whether each meter was visible to none, one, two, or three or more communications towers (Table 2). The project tool furthered this analysis by selecting and consequently exporting out all meter records in which there was no visibility to any of DCUs within its group. Five communications towers were then added to the network to provide coverage to the meters with no visibility to any of the proposed DCUs. The results were displayed geographically and represented in a table, successfully capturing a broad overall analysis that opens the door for speculation as to how and why this particular network would perform at the level that it did as well as how to improve upon this project with the specification of a more strategic network layout.

At the point in which it was determined that the proposed smart grid network consisted of a total of 32 DCUs that provided coverage to 94.2 percent of meters in the City of San Luis Obispo, there were several options to consider in order to increase the percentage of meters with visibility. The most likely option to end the project using the least number of DCUs would have been to relocate the positions of the current communications towers and by trial and error attempt to gain visibility to a greater number of meters while adhering to placement standards presented in this project (i.e. located at the edge of a publicly-maintained road). This procedure would have also been significantly more time consuming and likely diminished the automated nature of the tool proposed in this project. One of the most significant considerations in formulating this project was decreasing the amount of time spent in trial and error procedures when building a smart grid network. Another option for increasing the meter coverage percentage without adding DCUs to the network would have been to increase the height of the existing communications towers. This procedure, although the easiest to deploy, is likely the least effective in increasing meter coverage percentages and increases the potential for customer complaints, as higher communications towers mean greater visibility to the public. Adding height can, however, in some circumstances lead to the development of a network that maximizes placement and could, in tandem with relocating DCU placements, result in covering all meters using the fewest number of assets. The final option— to add DCUs into problematic areas— was an expedient and effective means for boosting meter coverage percentages, but may or may not result in deploying the fewest number of assets. This option was chosen for this project as a result of its adherence to a relatively automated process and its effectiveness in bolstering meter coverage percentages. There is one additional means for increasing meter coverage percentages— the use of a location-allocation procedure involving processing of all potential alternative raster cells and selection of the most optimal computed locations according to the best visibility results, a process detailed further in Section 5.3.

As an important aspect in siting DCU assets, an obstruction and tree canopy analysis was carried out by way of heads-up digitization of foliage characteristics based on opacity and density appearance as perceived from 2012 aerial photographs of the City of San Luis Obispo. A solar obstruction analysis was carried out in order to confirm efficacy of the solar panels that DCUs draw power from. Analysis was carried out to ensure that heavy tree density regions were avoided in network creation procedures. Potential site locations were also evaluated for distance to power lines in accordance with CPUC determination that a site must be more than 10 ft from powerlines for safety reasons.

5.2 Potential Project Weaknesses

5.2.1 Roads, Buildings, Meter Locations and Utilities

As is the case for all projects rooted in geographic analysis, there were inherent imperfections embedded in the development and character of the tools and their subsequent application to propose a smart grid for the City of San Luis Obispo. Roads were buffered to 40 feet in width and although this is the most common street width, it is not the standard under all circumstances. Building footprint data were digitized from 2011 aerial imagery. Changes that have occurred in the past three years would not be included in the housing data, one of the most critical data elements in analysis procedures. The procedure of snapping utility meters that are primarily located at street level in front of houses to the edge of the nearest house is the best approximation but may not capture the correct location under all circumstances. Data for powerlines was restricted to high power overhead lines and did not include all standard powerlines. Comprehensive powerline data in southern California is maintained by Southern California Edison and difficult to obtain. Underground utility data representing potential construction interference was also not included in the proposed method because these data are maintained by SCGC and are considered confidential and not available to the public without paying a rental fee for temporary access. Underground utilities are an important consideration in that one or more holes must be dug into the ground in order to construct a communications tower.

5.2.2 Meters Visibility Analysis

This thesis project also incorporated a meter to communications tower visibility analysis to determine coverage potential to all meters in a region, but only included terrain, distance to DCU, and tower height in this part of the analysis procedures. The most significant addition to the tool would be variables for path loss related to obstructions. Path loss is a decrease in power of an electromagnetic wave as it travels through space and is affected by open air, obstructions, refraction, diffraction, reflection and absorption. Buildings and land cover were not included in tool processing procedures as a factor in path loss. Buildings could have been shaped into clutter data, or a file representing signal obstructions, and an equation for decibel loss, or loss in power or intensity, applied when interference occurred. This procedure will be covered further in the future work section below. Similarly, land cover categories could have been added to the analysis procedures and given specific weights for radio frequency obstruction with signal loss equations applied to each class.

5.3 Future Work

5.3.1 Overview

There are several potential directions to build on from this project. One area is the addition of variables that could have an effect on final construction procedures. Examples would be utility lines, enhanced canopy assessments, inclusion of keep-out areas such as military bases and home owners associations, enhanced meter location logic, or the incorporation of radio frequency software such as EDX Wireless into the analysis procedures. EDX Wireless is a software package that provides specific settings for radio frequency analysis between source and destination points, such as decibel gain and loss, atmospheric absorption, ground conductivity, climate type settings, and various model types that are applicable to numerous environmental and asset equipment scenarios. The software runs a model that incorporates terrain and clutter files as a basis for analysis. Specific relationships between source and destination points can be established for solving MCLP issues. This thesis project was intended to act as a foundation for the addition of applicable site acquisition variables that carry meaning to specific projects. It is a model for incorporating logic into the creation of network grids and for telling as rich of a story as is possible about individual meter positioning within a network and how it relates to DCU assets. This project was also a foundation for future field studies to evaluate the effectiveness of various techniques for predicting coverage results. Eventually multi-layered field readings such as meters communicating three out of five attempts per week could be incorporated into analysis procedures, successfully capturing meter-reading gray areas and furthering troubleshooting capabilities.

One potential future work path could be the incorporation of enhanced meter location logic. Although a general standard of front or front side location was adhered to in this project, more specific meter locations are likely to have been captured by any utility company. Meter location data would need to be transferred from meter reading team knowledge to geospatial dataset. More accurate meter locations would equate to a more comprehensive meter visibility analysis. For example, a meter location on the west side of a residence would be a deterrent to communication with a DCU to the east, as the house would slow propagation down and possibly inhibit visibility. Greater accuracy in meter location data coupled with a comprehensive path loss equation (Section 5.3.2) would allow for more realistic meters visibility results, as it is likely that fewer meters would maintain visibility to high numbers of DCUs (i.e. greater than four). Ultimately, utility companies may have to gather realistic meter location data from multiple sources in order to accomplish the objective of accurate data relative to building footprints, but smart grid network creation as potential future work would be greatly enhanced as a result.

Another significant area of potential future work is in proposing a network that provides coverage to all meters while using the least number of DCUs possible. This process would involve a location-allocation analysis that maintains the placement restrictions presented in this project. Optimal raster cells for visibility would need to be restricted to the edge of publicly maintained roads, be greater than 10 ft from power lines as well as located away from dense tree cover. One possibility for completing this analysis would be an application similar to the ArcGIS Make Location-Allocation Layer tool, which creates a location-allocation layer based on specific properties, which in this case would be visibility as opposed to the cost attribute deployed in typical tool process. Tool processing would be significant, as the process would involve an analysis on each raster cell and a choice of the most optimal cells within the study grid while being restricted to the placement requirements presented in this project.

5.3.2 Clutter Data and Path Loss Analysis

This thesis assumed that radio frequency propagated in the 450-470 MHz range from meters can travel through buildings unimpeded, an assumption that is not entirely true. In reality, radio frequency from meters loses a percentage of signal strength when passing through buildings. In order to incorporate buildings into an analysis using ArcGIS's Observer Point tool, building footprint data features can be run in ArcGIS's Edit Triangulated Irregular Network (TIN) tool to incorporate building heights into the NED raster. Polygon feature heights can be incorporated into and define the surface area of a raster elevation file. The NED data would first need to be converted into a TIN raster using ArcGIS's Raster to TIN tool. The difficulty, however, in incorporating buildings into observer point analysis is in answering the question of to what degree does radio frequency in the 450-470 MHz range slow down when passing through a building. It is possible to address path loss in clutter data in ArcGIS, and there have been three methods proposed to do so: (1) the Okumura model; (2) the Lee model; and (3) the Hata model. Each of these models is ultimately an equation applied as path loss for clutter data. The models vary in their flexibility for adjusting to the local environment and ability to focus on specific factors such as terrain, land cover, or urban features. According to Tafazolli (2013), there is no significant difference between the 900 MHz band and the 412 MHz band when it comes to penetrating difficult indoor environments with meters located behind walls. Therefore, future work may consist of choosing a model that may be appropriate for the local environmental conditions and applying it as path loss to the clutter data.

Path loss as it relates to land cover may require a different approach. Qing (2005) formulated an approach that calculated path loss for land cover by grouping the data into three classifications: forest, grass, and residential. Each was assigned a path loss weight value, with residential being much higher than forest and grass. In modeling clutter data, each obstacle between source and destination was given a point and summed to estimate the total number of obstacles in the path. The elevation value of each pixel in the clutter data was determined and compared to the radio line-of-sight at that location. If the clutter data elevation was higher, a blockage was counted as a point. The total blockages in the path were considered as path loss in determining if there is visibility between source and destination. The final cumulative result of terrain variance, land cover diversity and distance from transmitter were figured into line-of-sight analysis. Low frequency wavelengths such as the 450-470 MHz range are best at penetrating building walls and reaching difficult locations, but calculating path loss for buildings and other clutter data nonetheless needs to be achieved by choosing an appropriate means of accounting for signal strength loss as it relates to various environmental obstacles in line-of-sight analysis.

Building a network of communications towers that provide coverage to all utility meters in a region requires knowledge of line-of-sight dynamics, obstruction potential, construction feasibility, and meeting the needs of a city using MCLP procedures. Ultimately, bridging the gap between network strength and potential construction hindrances by way of geospatial solutions could save time, resources, and money while carrying out projects that increase grid efficiency, allow alternative energy to potentially flourish in the future, deliver energy usage insight to residential users, and ultimately lower carbon footprints.

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