A DISTRIBUTED RENEWABLE ENERGY SYSTEM MEETING 100% OF ELECTRICITY DEMAND IN HUMBOLDT COUNTY: A FEASIBILITY STUDY

HUMBOLDT STATE UNIVERSITY

By

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ABSTRACT

A SIMULATED DISTRIBUTED RENEWABLE ENERGY SYSTEM MEETING 100% OF ELECTRICITY DEMAND IN HUMBOLDT COUNTY

by Darrell A. Ross

A model of electricity supply and demand in Humboldt County, California over the course of one year is presented. Wind, ocean–wave, solar, and biomass electricity generation are simulated using available hourly data and efficiencies of extraction for each. Hourly electricity demand is simulated using US Census 2000 data and county load data. A simulated two-dimensional geospatial map of Humboldt County power distribution is updated each hour of the simulation as demand and supplies fluctuate over one year. Given zero input from fossil fuel power generation sources, the model will show that without sufficient transmission to import power in times of deficit, the intermittent nature of each renewable power source cannot be compensated for even when all are harvested simultaneously. The model goes on to show that with reasonable renewable power plant sizes and as transmission capacity increases, Humboldt County could not only meet 100% of electricity demand year round, but could become a net electricity exporter.

ACKNOWLEDGEMENTS

A year ago, I was not sure I would complete my thesis. I could not have reached this point without the constant support from my loving fiancee. Thank you for believing in me Sharyn. Thank you Dad for providing constant encouragement and reading so many drafts. Thank you Grandad for helping me get so far in school. Thank you Mom for believing in me.

I fear I may have wandered on forever were it not for the careful guidance of my advisor, Ken Owens. Thank you to my committee members, Chris Dugaw, Lonny Grafman, and Charles Chamberlin for their patience and time.

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INTRODUCTION

Every generation has wrestled with the question of the best policy for energy discovery, development, generation, transmission, and distribution. In the article, "Energy Strategy: The Road Not Taken?" Amory B. Lovins (1976) discussed two possible energy paths the U.S. could take to meet energy demands: the *hard* or *soft* energy path. The hard energy path was that which involved meeting ever–increasing energy demands by seeking out every last vestige of oil, gas, coal, and uranium. As demand spirals upwards, supplying the world would require destruction of ever more remote and fragile ecosystems all for a finite fuel source. The soft energy path involved increased efficiency in our use of energy which could level out demand, matching energy production to end use, and producing energy from many diverse soft energy sources. Lovins defines soft energy sources as renewable energy flows like sun, wind, forest biomass, and agricultural wastes, which run in cycles unlike finite resources whose flows are a straight line from harvest to disposal (Lovins, 1976).

The Lovins article came at a time when the U.S. Congress was evaluating future power generation strategies. His critics, proponents of nuclear power and fossil fuels, argued that not meeting increasing energy demands would lead to an economic crisis and insisted that both hard and soft energy paths could be followed. Lovins asserted the paths were mutually exclusive given the political environment required for each path (Nash, 1979). Now, thirty years later, the drive to replace petroleum has risen swiftly as the resource grows scarce. Costs to access reserves within our own boundaries have risen, and attempts to acquire the resource from other countries have come at the cost of lives and our global reputation (Bradford, 2006). The hard energy path, as foreseen by Lovins (1976), has become politically undesirable and economically unsustainable when compared to the soft energy path. Wind and solar power have reached utility–grade and new generation is being installed at record rates. Ocean–wave energy research is taking place around the globe; the first commercial wave energy converter (WEC) farm is the Agucadora 2.25MW farm of Pelamis WEC's installed in September 2008 off the coast of Portugal (Pelamis, 2009).

Gasoline prices in the summer of 2008 gave the general population and auto–makers a glimpse of extreme costs that could arrive should we not seek energy independence through renewable means. Sport utility vehicle (SUV) sales nearly ground to a halt while demand for vehicles with good fuel economy climbed (Bunkley and Vlasic, 2008). The automotive industry is responding with increasingly fuel–efficient vehicles including hybrid electric vehicles (HEVs) and recently announced plug–in hybrid electric vehicles (PHEVs) which can go up to thirty miles on pure electric before switching over to gas (Nocera, 2008).

All of these factors point towards an inevitable new energy structure much like Lovins' soft energy path. When Lovins laid out his initial plan, he explained that as the country progressed down one energy path, it would become increasingly more costly to switch to the other path (Lovins, 1976). In 2008, Google Inc. teamed with General Electric and suggested the changes necessary to effectively switch the USA to a soft energy path will cost $\$3.86$ trillion. Their "Clean Energy 2030 Project" lays out an ambitious goal of 100% of electric power generation in the USA from renewable sources by the year 2030. A key component of the Clean Energy 2030 Project involves installing a new electrical power transmission backbone in the U.S. (Greenblatt, 2009).

The current aging electricity grid, the system of overhead wires, underground cables, and submarine cables used to deliver power, relies on centralized power generation (Casazza and Delea, 2003). Transmission lines take power from centralized sources to substations which transform the power to lower voltages and send it out on distribution lines to customers. Most distribution lines are radial, meaning that to trace a route out of the substation on a distribution line, it would not be possible to loop back to the substation. In order for distributed generation to happen, new transmission lines must be constructed to attach the generation to the transmission system. Some portions of the grid are nearly sixty years old, posing safety and reliability risks (Casazza and Delea, 2003). Depending on geographical location, transmission lines are owned by different power companies and, although the need for a new backbone is generally accepted, the construction of such a backbone needs to be orchestrated by a large cross section of power companies (Casazza and Delea, 2003). Humboldt County has four transmission lines through which it can transmit a maximum of 70MW of power (Zoellick, 2005). Two 115kV lines coming from the east provide for primary transmission and two 60kV lines coming from the south and northeast provide distribution and backup transmission (PG&E, 2009b).

Given that a new grid backbone is necessary for distributed generation to work, I will not consider grid–related calculations in this thesis. Substations and transformers are not needed to estimate total power supply and demand. In fact, the calculations are the other way around; demand is needed in order to design substations and choose transformers. Assuming that a new transmission and distribution system is available, an immediate question arrises, is there enough renewable energy available? The short answer is yes. To give you an idea of the quantity of power available from one source, let us do a short exercise. Humboldt County covers roughly 3500 square miles. If 0.1% of Humboldt County was covered in solar panels and conservative estimates for power generation are used[1], 3.5 square miles in solar panels would be required and, in 2008, would have generated approximately 1287 GWHrs. According to the load shape file provided by Marruffo (2009), the total electricity use in Humboldt County for 2008 including residential, commercial, and industrial electricity use was approximately 990 GWHrs. While there is clearly enough solar energy

[1] Solar insulation for 2008 retrieved from HSU's solar radiation monitoring station. Solar panels efficiency assumed to be 10%.

available, it is only available when the sun is shining. A followup question then, is given that large storage solutions are non-existant at this time, can Humboldt County be powered twenty–four hours per day year round on renewable energy?

The answer here is not so readily available. In order to cover nighttime power demand, we turn to wind, ocean–wave, and biomass.

- Bear River Ridge in south–western Humboldt County has been identified as one of the top ten best wind resources in California. According to Zoellick (2005), more than 400MW of wind resource is available there. Shell WindEnergy Inc. had planned the installation of a 100MW wind farm on the ridge (Cooper and Sanzenbacher, 2006). Since Humboldt County transmission capacity is limited, Shell WindEnergy Inc. (2007) decreased the system size to 70MW and has since canceled the project altogether even though the wind resource would have easily supported twice the 70MW farm. This model uses a 140MW wind farm, twice the size of Shell WindEnergy Inc.'s planned 70MW farm. A 30% capacity credit for the 140MW wind farm would have led to energy production levels of approximately 369 GWHrs in 2008, more than one third of electricity demand assuming 2008 levels (Gipe, 2004).

- Finding numbers for wave power is more difficult than for wind power. Pacific Gas and Electric (PG&E) is in the permitting process to begin the WaveConnect project off the coast of northern Humboldt County. They propose an approximately five square mile section of ocean supporting a 50MW wave farm. Using point source WEC's, device parameters provided by von Jouanne (2004), and ocean–wave data for 2008, a 50MW wave farm would produce approximately 128 GWHrs in 2008.

- Biomass power plant capacity for Humboldt County, including the Fairhaven Power Plant, the Humboldt Redwood Company Plant, and the Ultrapower 3, comes to approximately 64.3MW (Zoellick, 2005). Assuming a capacity of 75% and constant operation, 423 GWhrs of power could be produced in one year.

That is a total of 920 GWHrs of electricity produced by wind, ocean–wave, and biomass generators, or 92% of annual power demand.

Adding solar power to these three renewable sources, there is clearly enough power available on an annual basis given conservative estimates and reasonable generation capacities. The final question and the goal of this thesis: Is renewable energy available in a timely manner? That is, given hourly data for 2008 for wind, ocean–wave, and solar power supplies as well as hourly demand data, can Humboldt County be powered by renewable energy sources continually for the whole year?

LITERATURE REVIEW

The original inspiration for this model are the ten and twenty year Generation Expansion Plans (GEP) created by power companies to investigate how to expand power generation while optimizing transmission and distribution. Most GEPs, based on mathematical models, use optimization routines covered in depth by Hillier and Lieberman (2005). A mathematically framed full GEP is out of scope for this thesis, but model components of possible end scenarios for a Humboldt County GEP are presented.

A good introduction to electricity systems and the power grid is helpful, and can be found within Casazza and Delea (2003). A more technical look at the power grid by Schavemaker and van der Sluis (2008) provides far more detail than is needed.

Available renewable resources and current power infrastructure and grid statistics in Humboldt County are well documented by Zoellick (2005). Each power source is briefly addressed by Schaeffer (2005). While understanding the mechanics behind each renewable source is not vital, a rudimentary understanding of each is necessary.

Solar insolation dynamics are covered well by Duffie and Beckman (2006). Of note are various insolation types, including global horizontal and direct normal as well as diffuse. This thesis uses global horizontal insolation.

Wind for power production is well documented by Gipe (2004). Instead of using wind power conversion equations to estimate available power within the wind and then using an efficiency of extraction, this thesis uses the power curve for an existing 2MW wind turbine built by Vestas (2009).

Wave energy is briefly covered in one chapter by Stewart (2008). A good overview of wave energy conversion (WEC) devices and research taking place worldwide is available from Thorpe (1999). The specific WEC used in this thesis is covered in an unpublished report by von Jouanne (2004). In the report, von Jouanne states that the specifications covered were later incorporated into the now patented and proprietary AquaBuOY™ by Finevera.

Biomass generators in this model are assumed to be boilers which are covered in depth by Sonntag et al. (2003). A detailed understanding of boilers is unnecessary since the biomass plants in this model are operated at a constant rate. The model assumed the biomass generators to have the ability to ramp up and down at constant efficiency. Biomass fuel load and efficiency of burning wood waste are out of scope for this model.

Available energy models seek to model power systems in greater detail than was necessary here, often taking into account details such as the brand name of each power generator along with the manufacturer. Several such models are available from the National Renewable Energy Laboratory (NREL, 2009) and can be used to model small power systems for households or farms. Available commercial grid modeling software like WindMil by Milsoft (2009) or Network Management by AREVA (2009) seek to model every aspect of the power grid, which includes the many constraints of a centralized generation power grid. Since this model is built around a distributed generation countywide power grid, neither commercial grid modeling software nor small power system software packages are a good fit. Also common are papers that investigate specific small single source or hybrid power systems and their dynamics, like Riad Chedid (1997). A unique energy model that was considered is EnergyPlan, developed by Lund et al. (2004) in Denmark. EnergyPlan allows inputs to model an entire energy system including demands, power sources, costs, and more. The primary goal of EnergyPlan is cost analysis. Since this thesis is focused on analysis of available resources and not on cost, EnergyPlan was not considered appropriate. Like EngeryPlan, most large–scale models also seek to answer questions about cost (NREL, 2009).

METHODS

This thesis presents a one–year simulation of Humboldt County electricity demand met by power generated from renewable sources. Hourly supply and demand data were gathered from the time period January 1, 2008 through December 31, 2008. A geospatial model of Humboldt County is presented with the power supply visualized.

Algorithms

A map of Humboldt County was divided into a grid where each cell is 1.5 miles on a side. Cells outside county lines are unmapped. This results in a grid 40 cells wide by 70 cells tall. Each cell is powered from one electrical power source, delineated by color, where black is unpowered, brown is fossil fuel, red is imported power from outside Humboldt County via transmission lines, purple is wind, yellow is solar, green is biomass, and blue is ocean–wave. This map displays the status of the supply and demand in each cell for the current hour at a glance. Figure 1 shows the model map of Humboldt County.

For each cell in the county, we calculate the straight line distance to each power source, as shown in Figure 2. The list of distances to power sources for each cell is sorted nearest to furthest. Once all distances are known for each cell, three passes are made through the entire grid of cells. The Matlab code for the distribution cycle is in Appendix A in the file *gepDistSteadyState.m*[2]. Each loop (or pass) through the cells assigns each cell to a specific power source based on a different set of criteria. The quantity of available power from each source is shown in Figures 3(b), 3(d), 3(f) in bright color while the quantity of power assigned to cells is shown in faded color. Note that there are two solar plants, three biomass power plants, and four transmission lines.

[2]The original inspiration for the model was a Generation Expansion Plan (GEP), thus the “gep” prefix to all the code files. A ten or twenty year GEP is created by power companies to estimate necessary expansion.

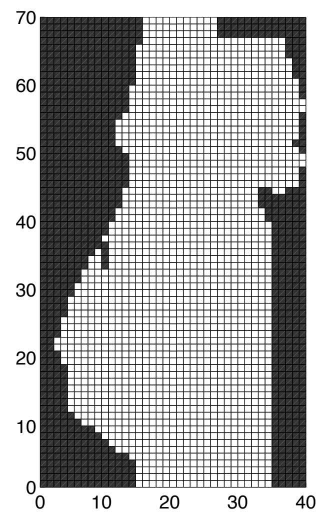


Figure 1: Model layout of Humboldt County, each cell is 1.5 miles on a side. The county is approximately 60 miles wide and 105 miles tall.

1. In the first loop, the results of which are shown in Figure 3(a), each cell is assigned power from its nearest source regardless of whether or not that source has power available. This usually creates power deficits among some sources. In the case of Figure 3, it is 1:00AM so that solar power is assigned to cells even though none is available as is detailed in Figure 3(b) where the faded yellow shows demand from solar power but there is no bright yellow showing supply. Another clear deficit is the second biomass plant which has 35MW of demand and only 18MW of supply.

2. In the second loop, power deficits created in the first loop are remedied. This is accomplished by isolating all cells powered by sources in deficit and passing through them beginning with those that were furthest from their power source in deficit. This is exemplified in Figure 3 where the cells formerly powered by solar and biomass plants in deficit were reassigned. Figure 3(d) depicts the shift in power supplies. It

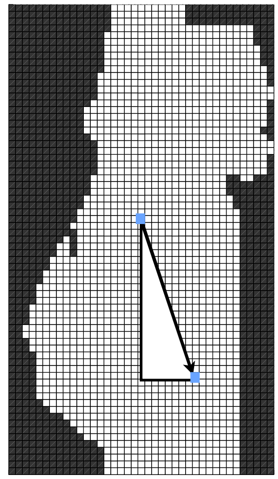
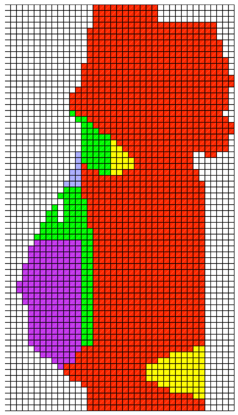


Figure 2: Distances from each cell to each power supply source are calculated using the Pythagorean theorem. Each power source has a designated source cell to which all distances are calculated.

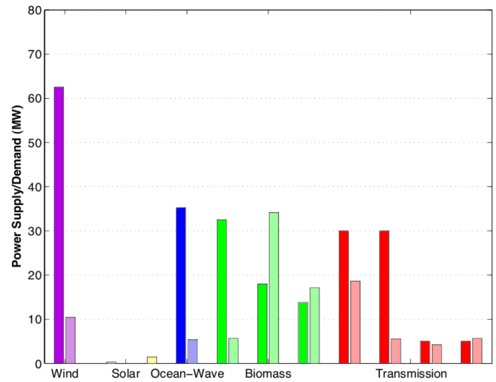
is evident that none of them are in deficit. If no new sources are available, the cell is designated as blacked–out.

3. In the third loop, intermittent power supplies are exausted. Cells powered by on–demand sources like biomass and imported power via transmission lines are reassigned to draw power from their nearest available source that cannot supply power on–demand (wind, solar, or ocean–wave).The algorithm uses distance to pass through the cells, this time reassigning those furthest from on–demand sources to available intermittent sources first. The final results shown in Figure 3(f) indicate that all wind and ocean–wave power is being used, no solar power is being used, and only a small amount is drawn from biomass and transmission lines. This power supply state can also be seen in the first hour (first column) in Figure 29 on page 42.

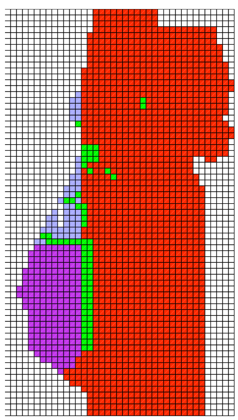
In each loop, the cells are processed in order of distance to their sources. Without delving into power loss through transmission and distribution, this three–loop sequence allows



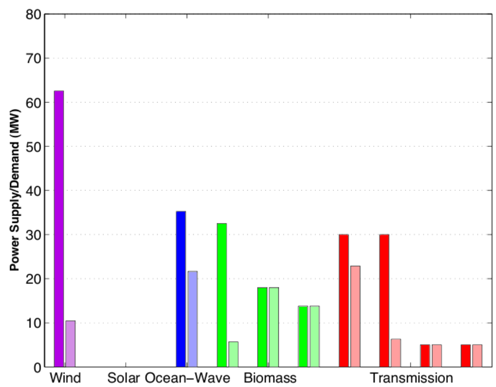
(a) Loop 1



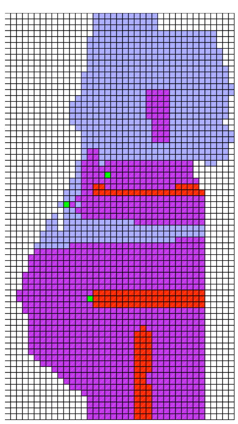
(b) Nearest Supply Source



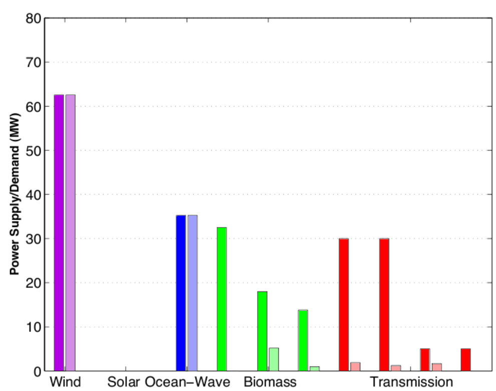
(c) Loop 2



(d) Nearest Available Supply Source



(e) Loop 3



(f) Nearest Intermittent Source

Figure 3: The three loops that distribute power on January 1, 2008 at 1:00AM. For each plot, power sources are color coded with purple for wind, yellow for solar, blue for ocean–wave, green for biomass, and red for transmission lines. The county maps show which cell is powered by which source. The bar plots show how much power was available from each source (bright colors) and how much power was used from that source (faded colors).

the model to account for such losses while at the same time aiming for a minimum use of on–demand power. The result of the above three loops for January 1, 2008 at 1:00AM is visible in Figure 3(e). Only the image in Figure 3(e) is displayed in the model visualization. The other two images are purely to explain individual steps of the model. Next, new supply and demand data is retrieved for 2:00AM, the demand density map is calculated, each supply quantity is calculated and the loops begin again[3].

Supply

Current power supply for Humboldt County comes from 70MW of power imported to the county via transmission lines, the 137MW natural gas fired Humboldt Bay Power Plant, and two small biomass power plants totaling 50MW. Several power plants providing less than 1MW each were left out of this model (Zoellick, 2005). The peak demand in Humboldt County in 2008 was 166MW. Given the 70MW transmission line maximum, Humboldt County cannot import all needed electricity.

The supply sources for the model are biomass power through the burning of wood chips, wind power through the use of wind turbines, solar power through the use of photovoltaic panels, and ocean-wave power through the use of point source wave energy converters (WECs). The chosen sites, methods of extraction, and assumed levels of availability for each source are covered in the following sections. The Matlab code for the algorithms described in this section is in Appendix A in the file *gepSupply.m*. In this model, intermittent power supplies like solar, wind, and ocean–wave take priority over on–demand power like that available through biomass power and imported power via transmission lines.

[3]Ideally, an optimization routine would be used to distribute power but an optimization routine of this size would be an MS Thesis all by itself, and is therefore out of scope for this investigation.

Transmission

Humboldt County has four transmission lines capable of importing power, two 115kV lines coming from the east and two 60kV lines coming from the north–east and the south (Zoellick, 2005). The lines from the east were modeled as 30MW power supplies and the north-east and south lines as 5MW power supplies. Transmission lines import power which is assumed to have a higher carbon footprint than renewables, but this could change in the future. The transmission lines are delineated in the model as power sources over a straight line distance. In reality, the distribution lines could only come from substations where they meet transmission lines but assuming a new transmission backbone must be built, This thesis treats the transmission lines as if they could be tapped for power anywhere along their length. Their locations in the model are shown in Figure 4. Actual transmission lines do not run in direct straight lines and eventually converge. Due to model constraints and since the lines are modeled as power supply sources, they are drawn as segments covering portions of the county but not connecting to one another.

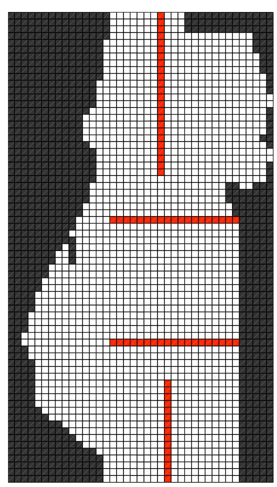


Figure 4: Transmission line locations in the model. The two lines running east–west are 30MW each while the north–south lines are 5MW each.

<u>Biomass</u>

Biomass power is already produced by two plants in Humboldt County: the 18MW Fairhaven Power Company plant in Samoa and the 32.5MW Humboldt Redwood Company plant in Scotia. There is also the 13.5MW plant in Blue Lake, the Ultrapower 3 (see Figure 5). The Ultrapower 3 was shut down in 1999 but was recently purchased by Continental Resources Solutions who will be using it again soon (Driscoll, 2008). Biomass fuel availability was assumed to be constant. No new biomass generation was considered in this model. Since biomass can generate power on–demand, its priority is above imported power via transmission lines but below wind, ocean–wave, and solar. Each plant is assumed to be able to run at a maximum of 100% capacity and able to ramp up and down at infinite rates[4]. Power output for each plant is set at a constant capacity. Any generation above needed levels is exported if transmission capacity is available.

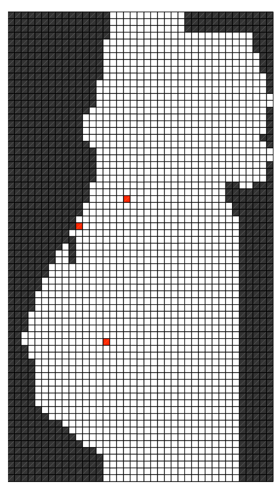


Figure 5: Biomass power plant locations in the model. The left–most plant is the Fairhaven Power Company 18MW plant. The southern–most plant is the Humboldt Redwood Company 32.5MW plant. The northen plant is the Continental Resources Solutions 13.5MW plant.

[4]In reality, biomass plants cannot ramp up and down at infinite rates nor with infinite efficiency, but modeling these rates is not within the scope of this model.

Wind

The best wind resource in Humboldt County is the Bear River Ridge in southwestern Humboldt. The Bear River Ridge location in the model (shown in Figure 6) is near Cape Mendocino, the western–most tip of the continental United States. Wind moves down the coast and roars over the ridge. Shell WindEnergy Inc. monitored the resource and originally planned a 100MW wind farm. After learning about limited transmission capacity within Humboldt County, they decided on a smaller farm. Since Shell WindEnergy Inc's wind data is proprietary, hourly wind data was obtained from the National Oceanographic and Atmospheric Administration's (NOAA's) Trinidad Head Laboratory through assistance from Michael Ives (January, 2009). The measurements at Trinidad Head were done at a height of 10 meters and Trinidad Head is 50 miles north of Bear River Ridge (shown in Figure 6 in green). Shell WindEnergy Inc. provided that their turbines would be 82 meters tall with 80 meter diameter blades and 2MW towers which closely resembled the V80 wind turbine built by Vestas (2009). Differences between the data site and proposed wind farm site were accounted for using the annual average 20m and 80m wind data provided by 3TIER (2009). According to 3TIER's FirstLook website, annual average 20m wind speed at Trinidad Head is 3m/s to 5m/s while the 80m annual average wind speed at Bear River Ridge is 5m/s to 8m/s. Dividing the average of Bear River Ridge at 80m by Trinidad Head at 20m yields the ratio used in this model 1.6. The power curve of the Vestas V80 Wind Turbine is approximated in Figure 7. Combining this data, the wind farm power produced is calculated as

$$= \quad (\text{Wind Speed}) * 1.6 * (\text{V80 Power Curve}) * (70\text{V80s})\,.$$

Wind speed data for January 1, 2008 and resulting power produced by a 140MW wind farm is shown in Figure 8. Annual output for the wind farm is shown in Figure 9.

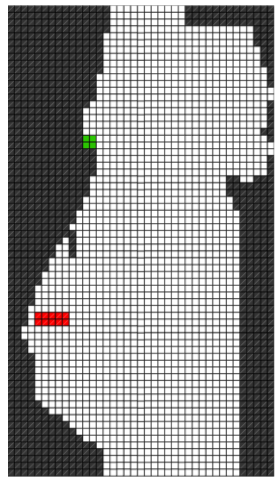


Figure 6: Wind farm location in the model with up to a 140MW capacity. Red indicates the location of the wind farm. Green shows the data source location of the Trinidad Head Laboratory.

Solar

Hourly global horizontal solar insolation data was supplied by the Humboldt State University Solar Resource Monitoring Station (SoRMS)(RESU, 2009). The location of the SoRMS atop the HSU Library is indicated in green in Figure 11. Global horizontal means the data assumes solar panels would be laid out parallel to the ground instead of tilted towards the sun as shown in Figure 10. Direct normal data is available with a calculation but this assumes direct insolation is available at all times. Photovoltaics (or solar panels) are used for the power plants in this model with an efficiency of extraction of 10% for each location. Large scale solar power plants are available in both solar thermal concentrator plants and photovoltaic plants. Solar thermal concentrator power plants require beam radiation while photovoltaic plants work with diffuse as well as beam radiation. Beam

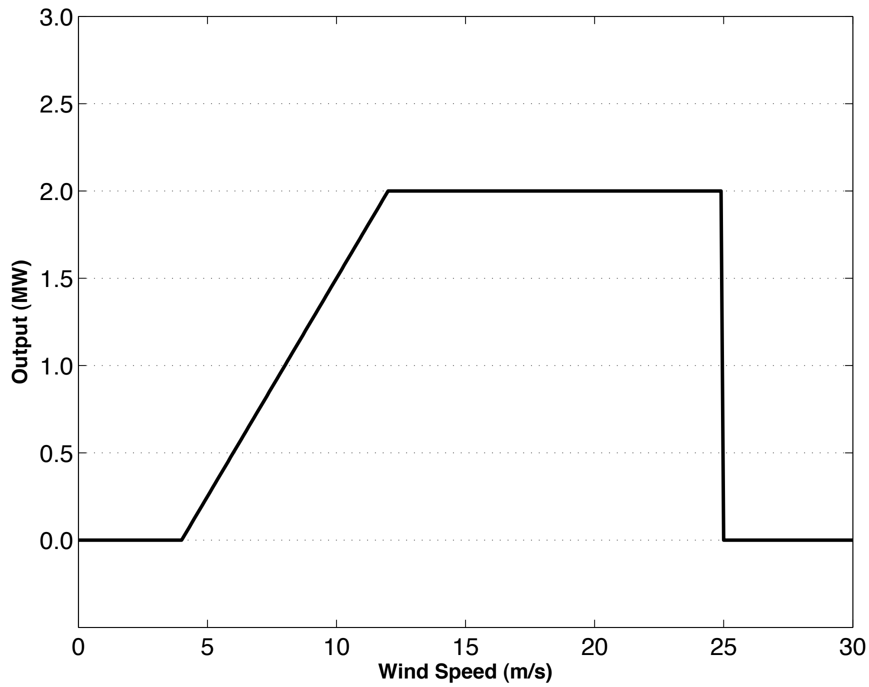
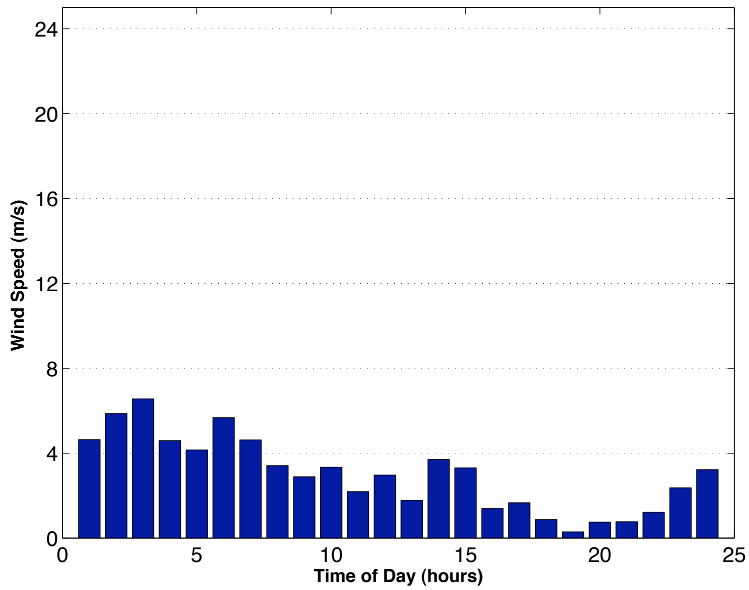
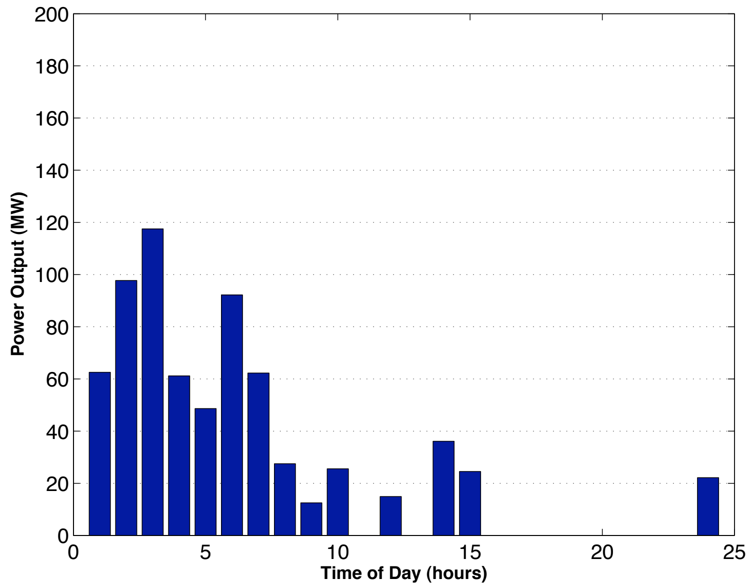


Figure 7: Vestas V80 power curve approximation used in this model. Wind speeds below 4m/s and above 25m/s produce no power.



(a)



(b)

Figure 8: Twenty–four hours of January 1, 2008. The wind speed data (a) is used to calculate the power output (b).

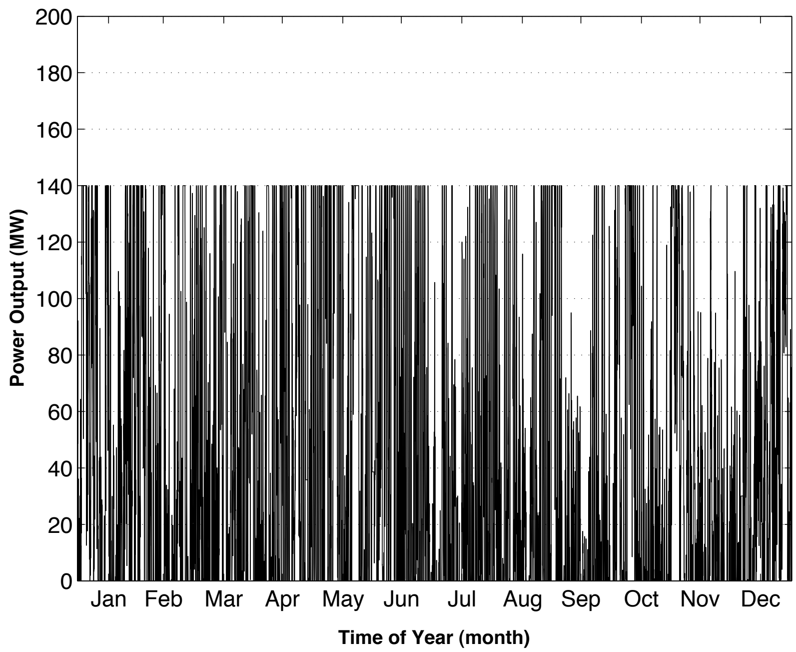
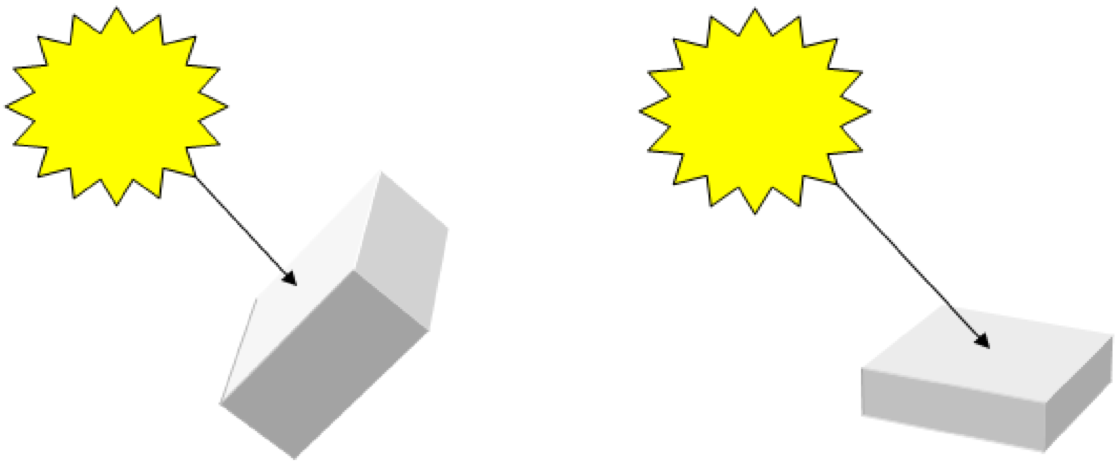


Figure 9: Hourly wind power plant output for all of 2008.

radiation is the direct rays coming from the sun (Duffie and Beckman, 2006). Given the often overcast weather conditions in Humboldt County, photovoltaics were used as they would still work without beam radiation. Two solar power plants of 25MW were chosen. Each 25MW plant covers approximately 250,000 square meters for approximately 100W per square meter. Locations for the plants were chosen to be inland and in areas with some demand at opposite ends of Humboldt County: Blue Lake and Redway (see Figure 11). Plant sizes were chosen so as not to take up too much space and not meet more than 50% of demand at peak output. Using the HSU SoRMS data provides a conservative estimate since the chosen solar regions are inland while HSU is on the coast where overcast skies are more common. Solar insolation data for January 1, 2008 and resulting power produced by the two 25MW power plants is shown in Figure 12. The annual output for solar power is shown in Figure 13.



(a) Direct Normal (b) Global Horizontal

Figure 10: A graphical comparison of Direct Normal (a) and Global Horizontal (b) solar exposure.

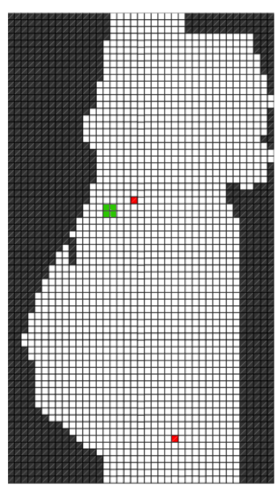
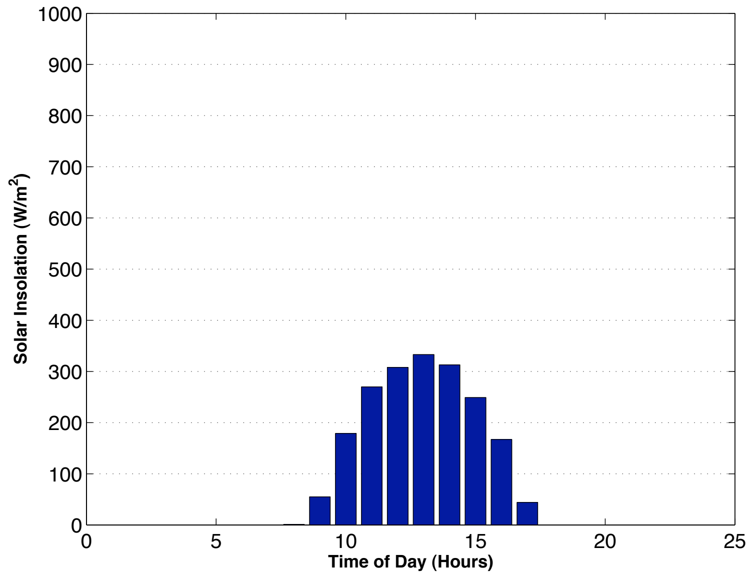
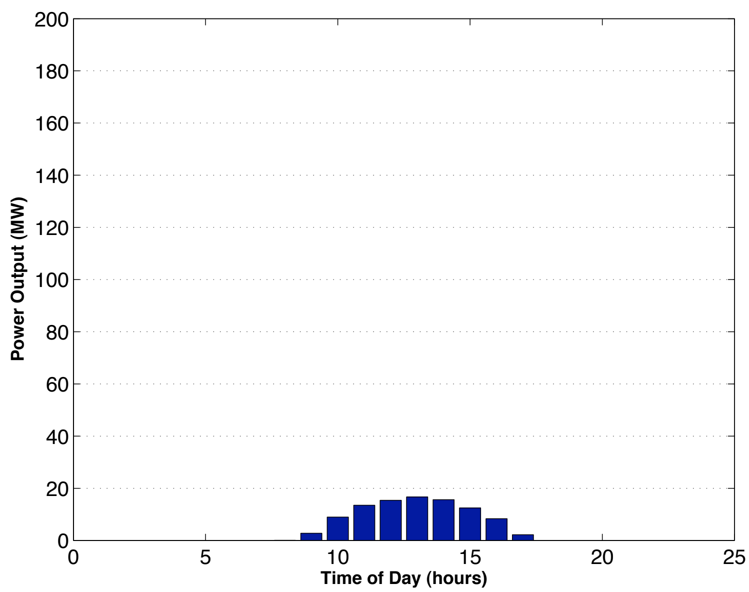


Figure 11: Solar power plant locations in the model. Red indicates solar power plant locations. Green shows the relative location of the RESU SoRMS where the data was collected. Each plant is built with a 25MW capacity.



(a)



(b)

Figure 12: Twenty–four hours of January 1, 2008. The solar insolation data (a) are used to calculate the solar power output (b). The vertical scale on the solar insolation plot is set to 1000W/m^2 to show how little insolation is available this winter day — the maximum insolation during the year is close to 1000W/m^2. Power output on the output power plot is set with a maximum of 200MW to show how little solar power was provided when compared to county demand.

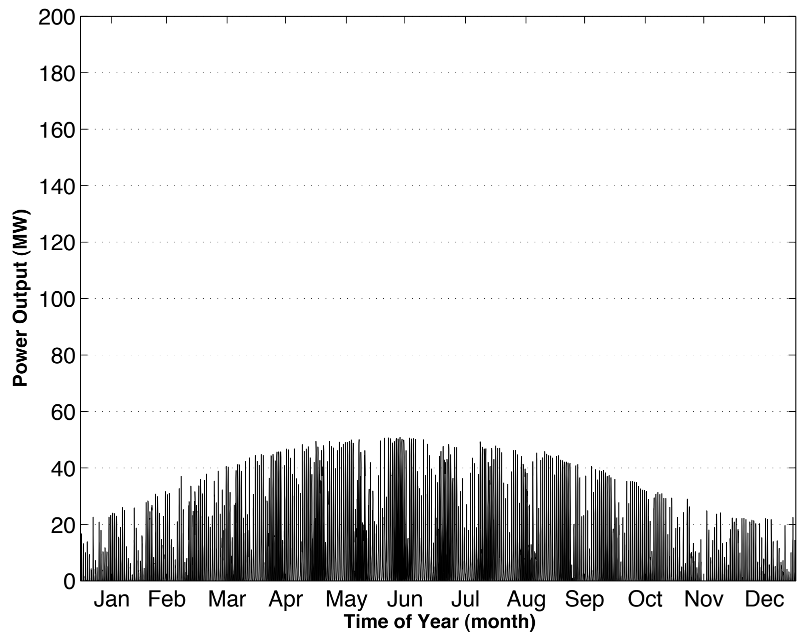


Figure 13: Hourly solar power plant output for all of 2008.

Ocean–Wave

Ocean–wave power technologies are in various stages of development worldwide (Thorpe, 1999). PG&E is in the permit stage for their WaveConnect project off the coast of northern Humboldt County with a goal of testing viability of several off–shore wave energy converters (WECs). PG&E's designated location was used for the modeled WEC farm (see Figure 14). Hourly wave mean height and period were supplied by NOAA Station 46212 which is located approximately 8 miles west of Eureka, identified by the green spot in Figure 14 (NOAA, 2009). The WEC chosen for this model is a point source device like a buoy tethered to the sea floor. The amount of energy available in an ocean wave can be calculated with Equation (1) (Stewart, 2008).

$$P = 0.48 * H^2 * T \tag{1}$$

where

$$
\begin{aligned}
P &= \text{power in kW/m of wave front} \\
H &= \text{mean wave height (m)} \\
T &= \text{mean wave period (s)}
\end{aligned}
$$

Professor von Jouanne (2004) provided calculations and efficiency of extraction for a point source buoy they had tested. Since point–source buoys float on a single point, directional factor has minimal impact. Given the available power, P kW/m and that the buoy intersects 20m of wave front, has a directional factor of 0.9[5], and an efficiency of extraction of 30% (von Jouanne, 2004), the power produced by a single buoy is equal to

$$= 20 * 0.9 * 0.30 * P, \tag{2}$$

$$= 5.4 * P. \tag{3}$$

Buoy generation capacity was set at 500kW based upon Ocean Power Technology's technology comparison page where their cost assumptions are based on a 500kW buoy (OPT, 2009). Extrapolating this to one buoy per 100m allows approximately 16 buoys per mile if only one line of buoys is deployed. Continuing this pattern for six miles gives us 96 total buoys with a maximum capacity of 48MW. Mean wave height and period data for January 1, 2008 and resulting power produced by the wave farm is shown in Figure 15. The annual power output for this wave farm is shown in Figure 16.

[5] Shore–based WECs have directional factors around 0.3. Since the buoy is a point away from the shoreline, it can generate power from waves traveling in any direction.

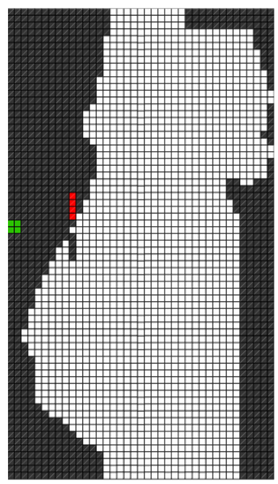
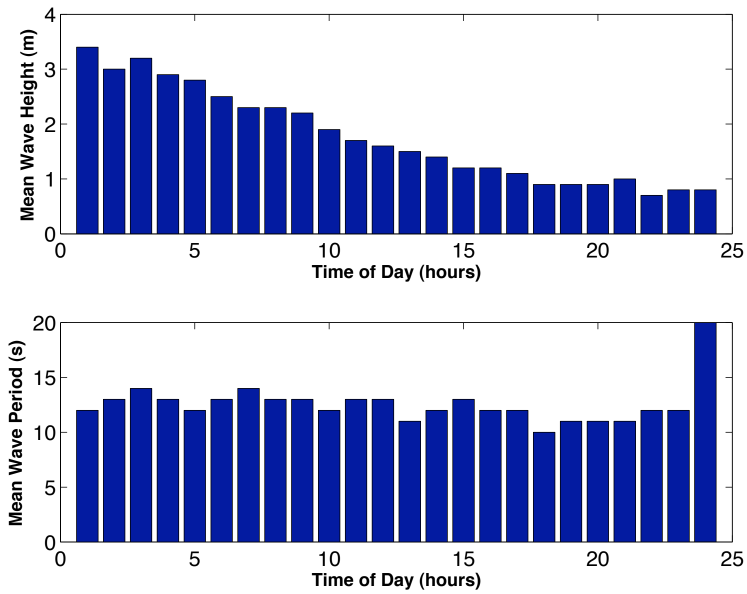
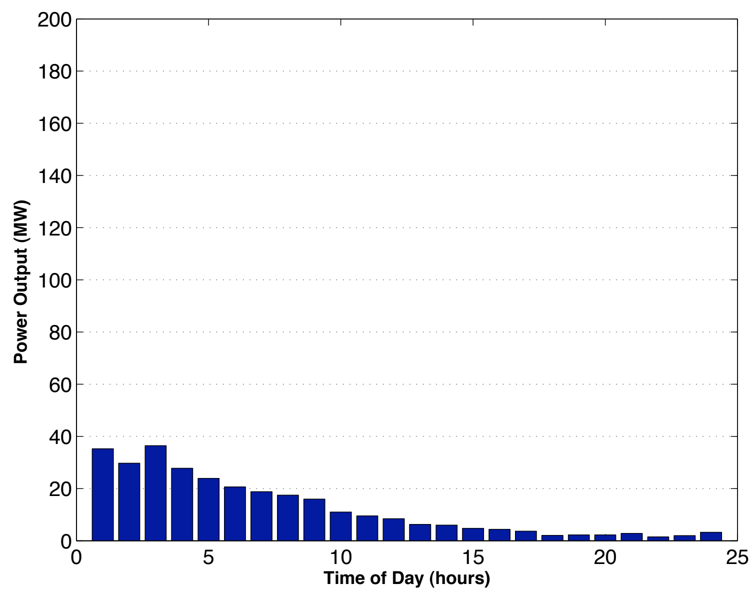


Figure 14: Wave farm location in the model. Red indicates wave farm location. Green indicates NOAA Station 46212 where wave data was retrieved from. An assumed 50MW capacity is used for the wave farm extending along six miles.



(a)



(b)

Figure 15: Twenty–four hours of January 1, 2008 (NOAA, 2009). The mean wave height and mean wave period (a) are used to calculate the wave farm power output (b).

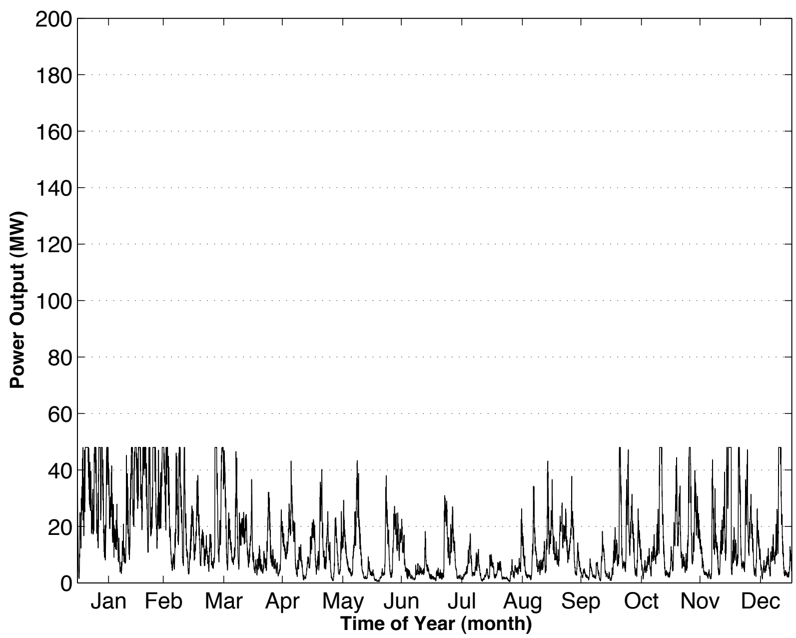


Figure 16: Hourly wave farm output for all of 2008.

Demand

A load shape file describing hourly demand throughout the year was provided by PG&E (2009a). The load shape for January 1, 2008 is pictured in Figure 17 showing a typical twenty–four hour electricity demand curve for Humboldt County. The annual load shape for Humboldt County is shown in Figure 18. Electricity use in Humboldt County for 2008 totaled approximately 990 GWHrs. Unlike other parts of California, the most densely populated coastal regions of Humboldt County do not have a hot summer creating high power demand from air conditioning units. Peak power demand in Humboldt County is during the winter due to heating needs (Zoellick, 2005).

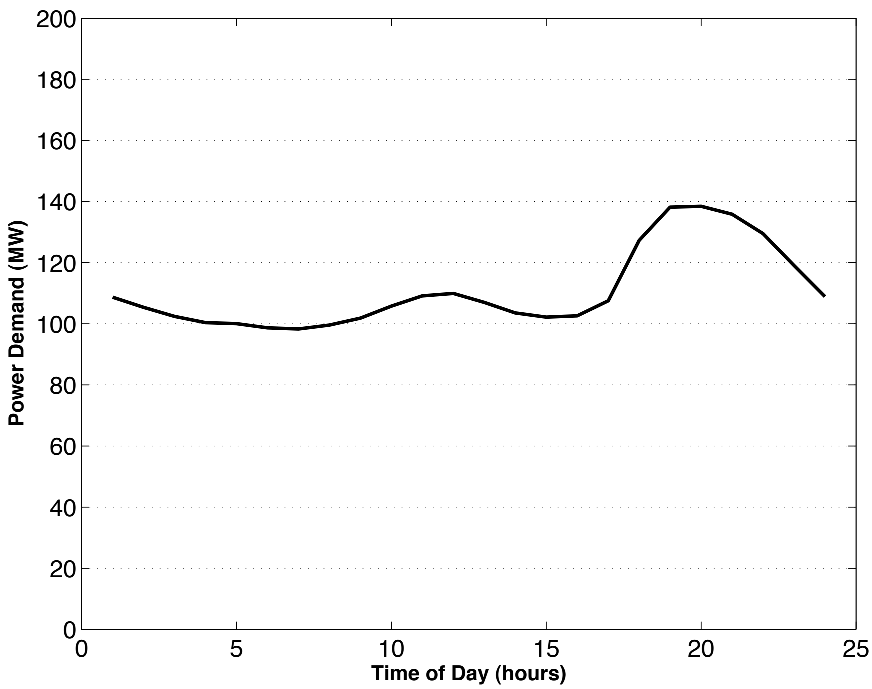


Figure 17: A 24–hour load shape for Humboldt County on January 1, 2008 (PG&E, 2009a).

US Census 2000 data was used to define a population density for each cell in the map of Humboldt County (Census, 2000). Most of the population of the county is centered

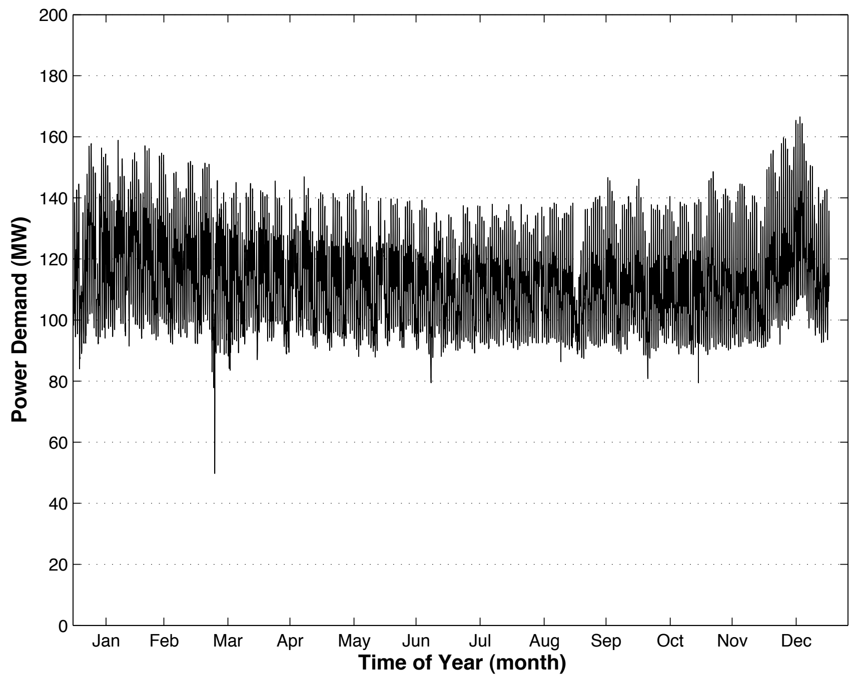
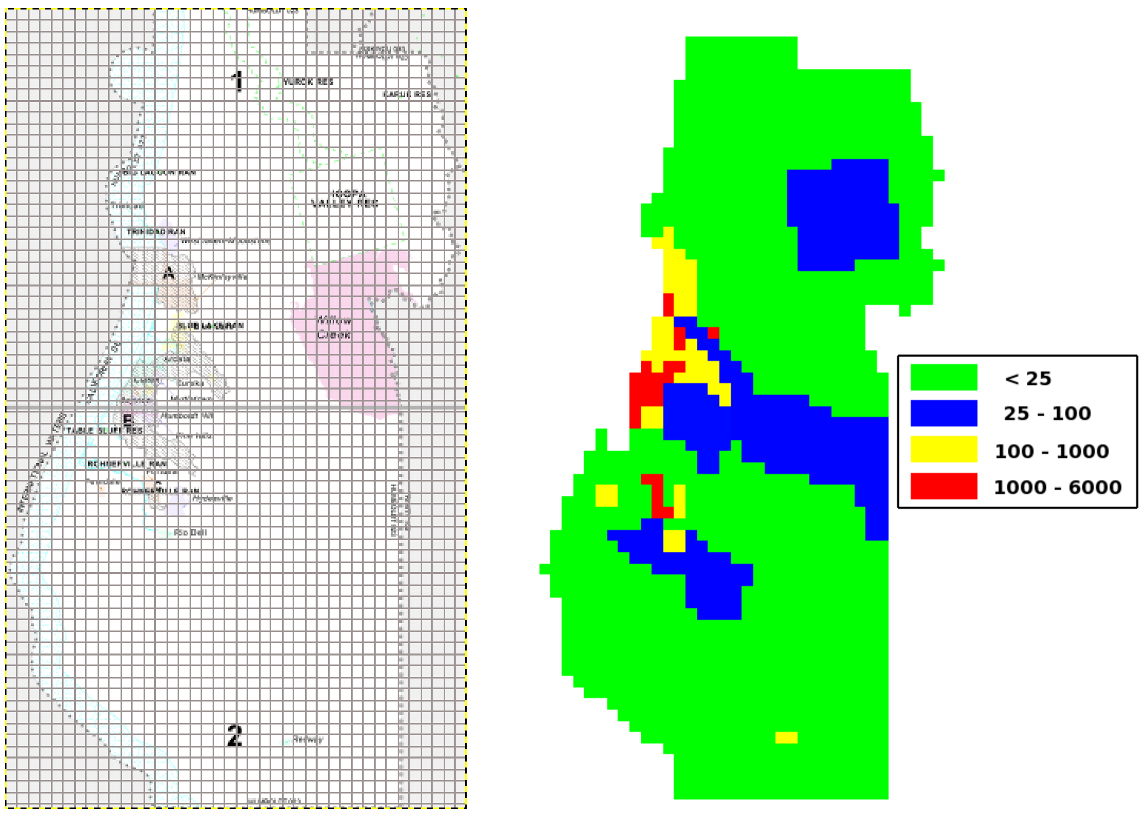


Figure 18: Annual load shape for Humboldt County (PG&E, 2009a).

around Humboldt Bay with a few smaller centers along major roads (see Figure 19). A grid overlaid on the U.S. Census 2000 plot for Humboldt County (Figure 19(a)) coupled with census data allowed the calculation of a population density map shown in Figure 19(b). The population densities shown are just a sample; the full data set is more complete. Population density multiplied by total hourly power demand allows us to define power demand for each cell each hour of the year. Cell demand for one hour is shown in Equation (4).

$$(\text{Cell Power Demand}) \quad = \quad \left(\frac{\text{Cell Population}}{\text{Total Population}}\right) * (\text{Total Demand}) \qquad (4)$$

Residential power demand accounted for 40% of demand in Humboldt County in 2008 while non–residential accounted for the remaining 60%. Determination of non–residential power demand locations was considered but left out for lack of available data.



(a) Census 2000 Layout (Census, 2000).

(b) Population Density in persons per cell ($2.25mi^2$).

Figure 19: (a) The U.S. Census 2000 map for Humboldt County and (b) a population density map of Humboldt County created using U.S. Census 2000 data (b).

ANALYSIS

Three scenarios were chosen for study using the proposed model.

1. Current Power System: the current power system in Humboldt County.

2. Only Renewable Sources: All demand solely met with renewable sources.

3. Net Zero Humboldt County: Demand is met with renewable sources while using transmission lines to cover short term power deficits and surpluses.

Each scenario was run on the following time periods.

1. 24 hours — January 1, 2008[6]

2. Winter — Sunday December 14, 2008 through Saturday December 20, 2008[7].

3. Summer — Sunday July 1, 2008 through Saturday July 7, 2008.

4. Full Year — January 1, 2008 through December 31, 2008.

Scenario One: Current Power System

In Humboldt County's current power system, which power source is given priority is based on cost. If PG&E can purchase imported power via transmission lines for less than they can generate power at the Humboldt Bay Power Plant (HBPP), then the HBPP runs at a lower rate. Conversely, if the HBPP is the cheaper source at the time, then they run the HBPP at a higher rate (PG&E, 2009a).

In this simulation of the current power system delineated in Table 1, transmission lines and biomass power are assumed to be cheaper than the HBPP and provide most of the

[6]January 1, 2008 was chosen because it is the first 24 hours of data.

[7]This week contains the peak demand hour at 166MW.

power while the HBPP serves as the peaking generator. This means the HBPP is ramped up and down as needed to meet the peak demand while transmission and biomass power supplies are held constant. Powering up the HBPP from a completely stopped state would take too much time to make constant starts and stops feasible so transmission line capacity for importing power is set low enough so that the HBPP can be *held in reserve* or remain powered at all times even if it is not running at full power. Biomass and transmission lines were each set at 75% of capacity for the duration of the scenario.

Power Plant	Plant Type	Size (MW)
Fairhaven Power Company	Biomass	18MW
Humboldt Redwood Company	Biomass	32.5MW
Transmission Lines	Transmission	70MW
PG&E Humboldt Bay Power Plant	Natural Gas	135MW

Table 1: Current Humboldt County power supply sources.

A twenty–four hour power supply plot is shown in Figure 20. The biomass and transmission lines run at a constant 75% capacity while the Humboldt Bay Power Plant oscillates with a low capacity of 6.22% and a high capacity of 35.61%. The twenty–four hour average here is 15.19%. The twenty–four hour cycle on January 1, 2008 is shown in Figure 21 in 2–hour pieces. Each time in the figure can be compared to the twenty–four hour supplied power plot shown in Figure 20. Transmission and biomass power supplies remain constant the whole time. As power demand peaks in the evening, the natural gas powered Humboldt Bay Power plant ramps up to meet the added demand.

Running the simulation for a week in the summer, from July 1, 2008 through July 7, 2008, the supplied power is shown in Figure 22. The Humboldt Bay Power Plant oscillates with a low capacity of 0.86% and a peak capacity of 32.68% averaging at 12.26%. The coastal climate in Humboldt County helps regulate summer temperatures making air

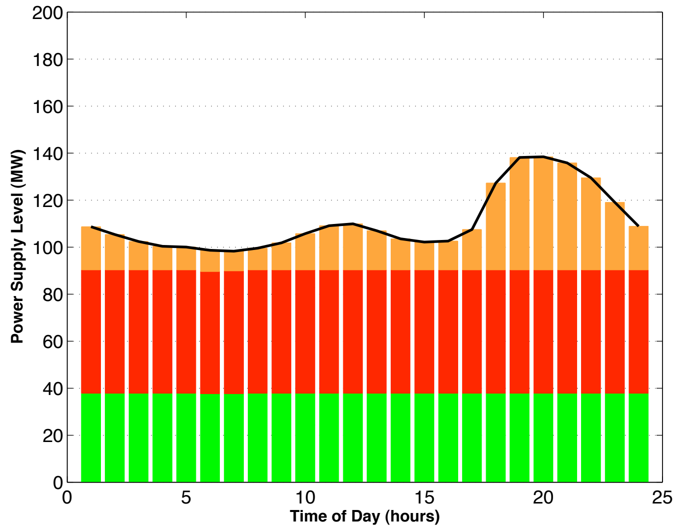
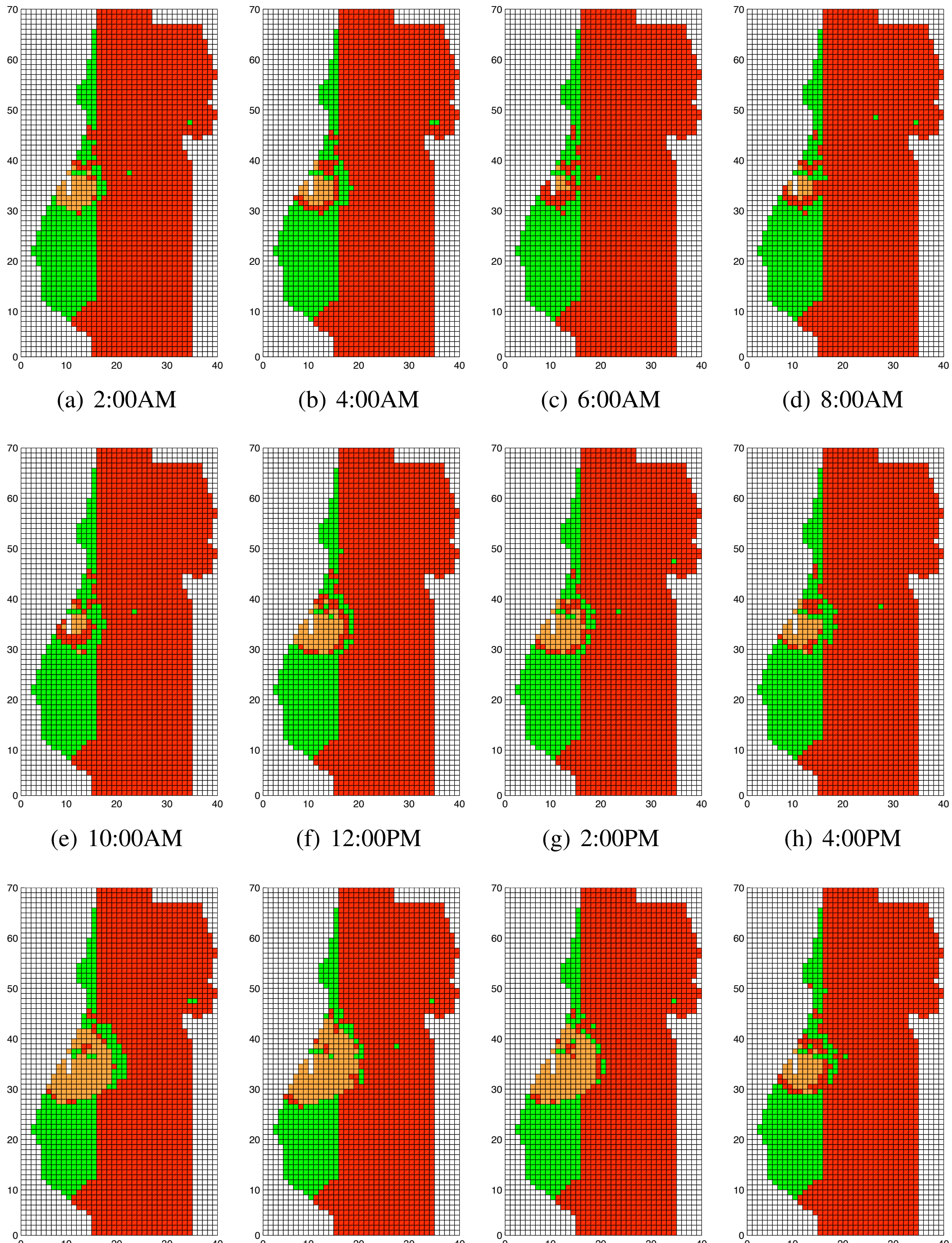


Figure 20: Supplied power for January 1, 2008 where green is biomass, red is transmission, and brown is fossil fuel.

conditioners, the main cause of summer peak power demand elsewhere in the state, unnecessary.

The supplied power for a week in the winter, December 14, 2008 through December 20, 2008, is shown in Figure 23. It is clear that Humboldt County power demand peaks in the winter but the difference is not too extreme. While the coast keeps the county cooler during the summer, it also keeps the main population centers, which are nearest the ocean, from freezing during the winter. The Humboldt Bay Power Plant runs with a low capacity of 7.2%, a high capacity of 56.42%, and an average winter capacity of 28.17%.

Running the simulation for the whole year gives too much data to read if plotted like the summer and winter supplied power plots. Instead, the hourly supplied power is sorted from highest to lowest and plotted as a load duration curve as shown in Figure 24. The Humboldt Bay Power Plant ran at an average capacity of 10% for the full year in this



(a) 2:00AM (b) 4:00AM (c) 6:00AM (d) 8:00AM

(e) 10:00AM (f) 12:00PM (g) 2:00PM (h) 4:00PM

(i) 6:00PM (j) 8:00PM (k) 10:00PM (l) 12:00AM

Figure 21: The geospatial distribution of supplied power on January 1, 2008. Since transmission and biomass supplies are constant, the natural gas supply (brown) expands as needed. These graphs correspond to the columns in Figure 20.

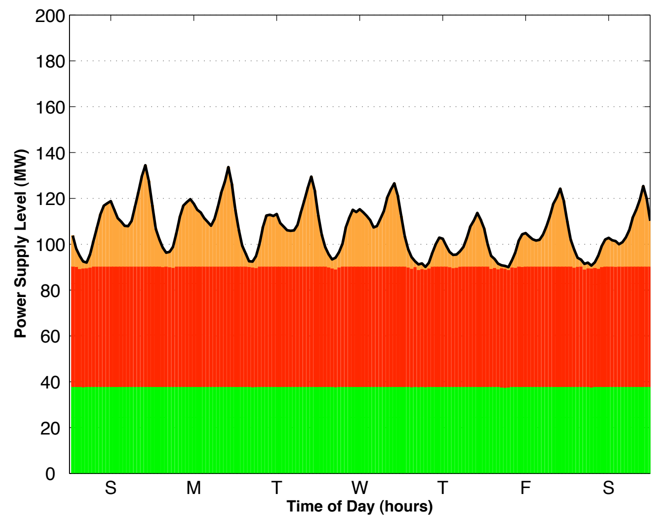


Figure 22: Power supplied in the summer from July 1, 2008 through July 7, 2008.

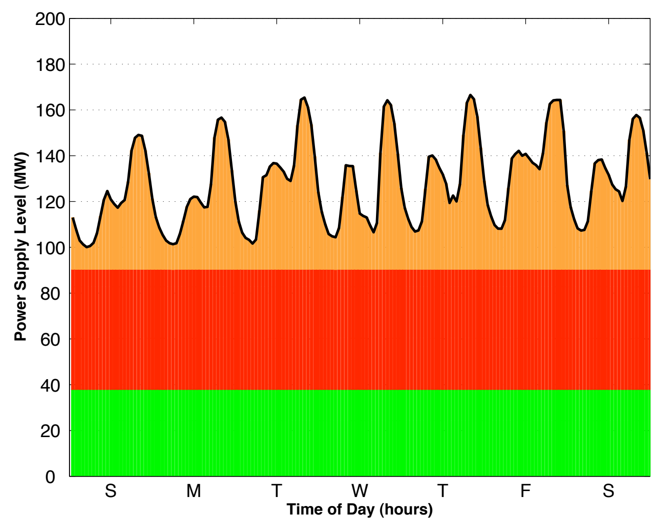


Figure 23: Power supplied in the winter from December 14, 2008 through December 20, 2008.

model. According to Zoellick (2005), the annual average capacity of the Humboldt Bay Power Plant in 2003 was 17%.

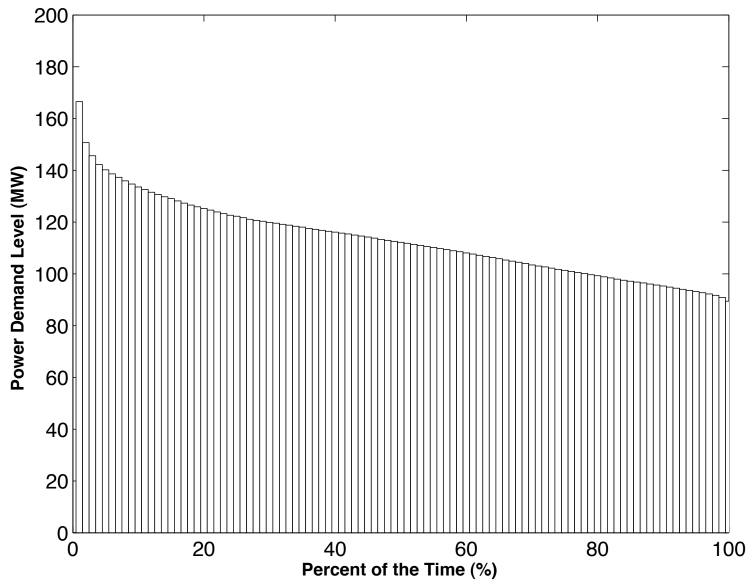


Figure 24: A load duration curve for power supplied in 2008. In this case, there are some times when power demand is less than the combined power supply of transmission and biomass (107.8MW). In order to keep the Humboldt Bay Power Plant running at all times, less power could be imported or the biomass plants run at a lower capacity.

Scenario Two: Only Renewable Sources

The power sources in this scenario are shown in Table 2. Using the initial renewable source generation levels covered in the Methods section, the result of powering Humboldt County by renewable energy sources only on January 1, 2008 is shown in Figure 25. The biomass power, the 140MW wind farm, two 25MW solar power plants, and a 50MW wave farm do not put out nearly enough power to meet demand. The simulation of data in Figure 25 is shown every two hours in Figure 26. The lack of sufficient power supply is quite evident.

Power Plant	Plant Type	Size (MW)
Fairhaven Power Company	Biomass	18MW
Humboldt Redwood Company	Biomass	32.5MW
Continental Resources Solutions Ultrapower 3	Biomass	13.8MW
Bear River Ridge (Shell)	Wind	140MW
Blue Lake PV Array	Solar	25MW
Redway PV Array	Solar	25MW
WaveConnect (PG&E)	Ocean–Wave	50MW
		291.3MW

Table 2: Renewable–only power supply sources, showing Actual and *Potential* generation facilities.

A full week of summer power supply versus demand is shown in Figure 27 while a full week of winter supply versus demand is shown in Figure 28. As would be expected, summer sees greater solar power production while winter sees better wind and ocean–wave resources. Daily demand continues its cyclic tendency peaking from around 6:00PM to 11:00PM. As shown plainly in Figure 25, the beginning of peak demand coincides with sunset. In the summer, the peak solar production coupled with the biomass plants running at 100% capacity meets demand at that point. Unfortunately, there is nearly no wind or ocean–wave power. Even though demand is higher in the winter, the large wind farm allows winter power demand to be met more often than that of summer.

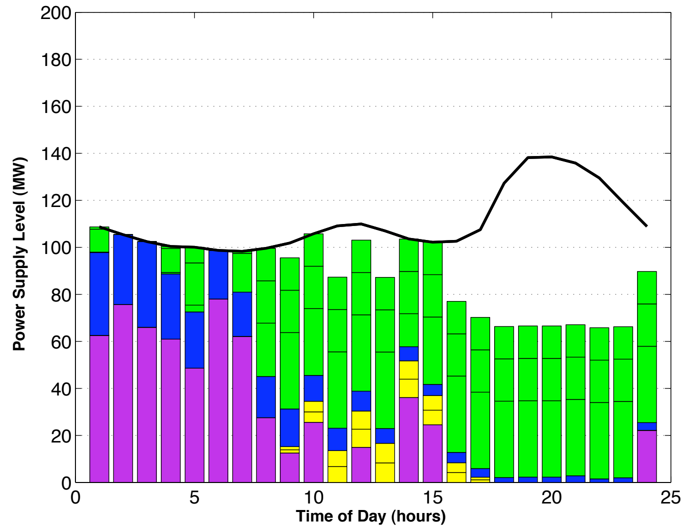


Figure 25: Power supplied for January 1, 2008 where purple is wind power, blue is wave, yellow is solar, and green is biomass. The black curve is power demand. It is clear that initial levels of power will not meet demand.

It is interesting that wind power helps meet electricity demand in the winter while solar power helps in the summer. The energy deficit for the summer week came to 3.439 GWHrs failing to meet demand 82% of the time. The winter deficit came to 3.442 GWHrs failing to meet demand 69% of the time. Even though winter demand was met more often, the greater deficits made total deficits similar to summer. In order to meet power demand year round solely with renewable sources, biomass power would need to be able to meet the demand in the absence of wind, solar, and ocean–wave supplies. But if we were able to meet power demand on biomass alone, then why consider other renewable sources? A possible solution not modeled here is energy storage.

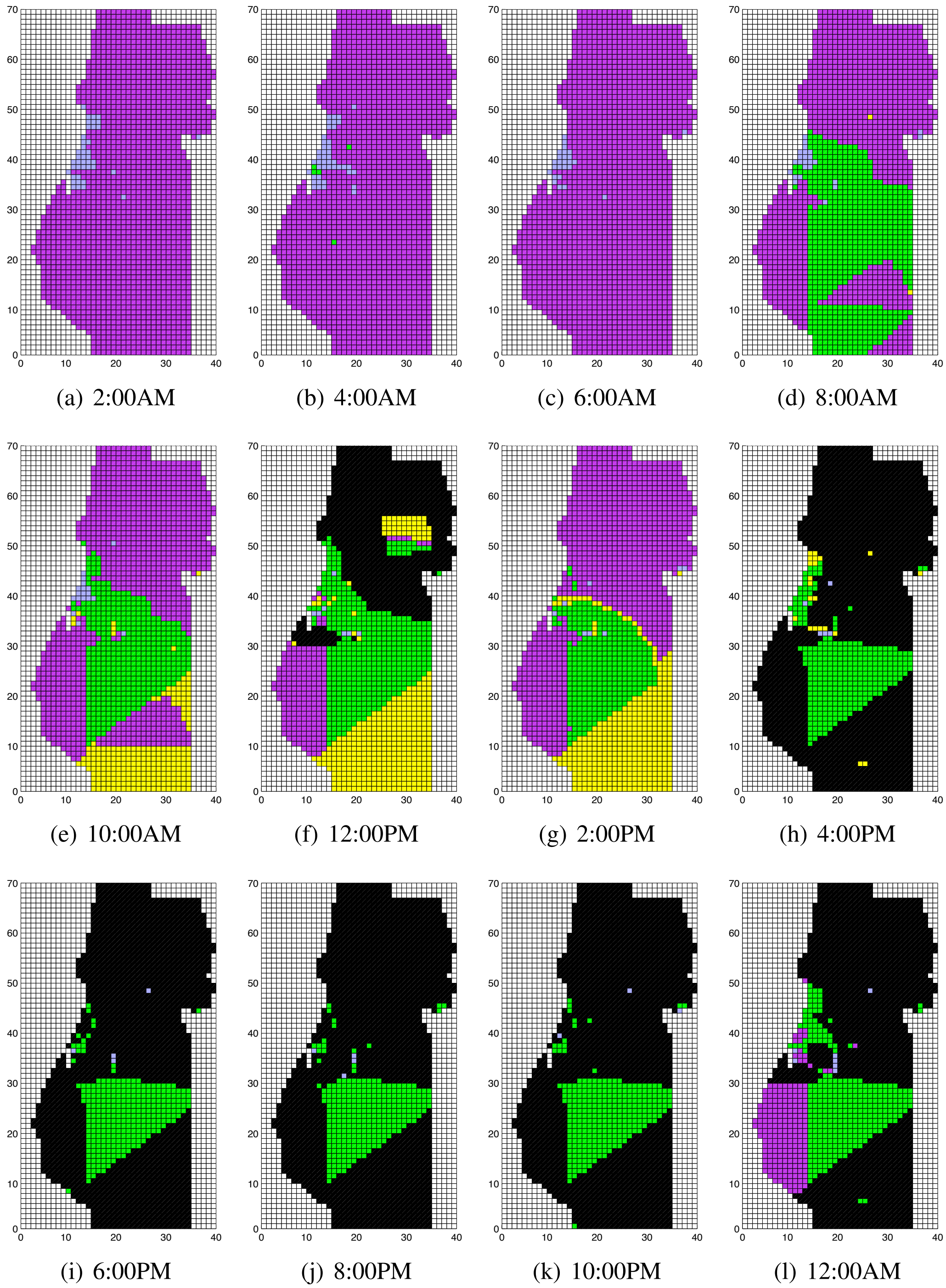


Figure 26: The geospatial distribution of supplied power on January 1, 2008. Notice that power is not met in the evening. These graphs correspond to the columns in Figure 25.

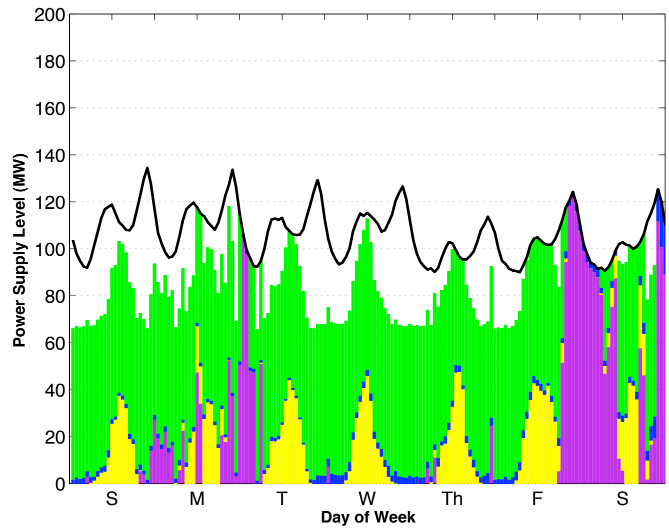


Figure 27: Summer power supply for July 1, 2008 through July 7, 2008. The black curve represents power demand.

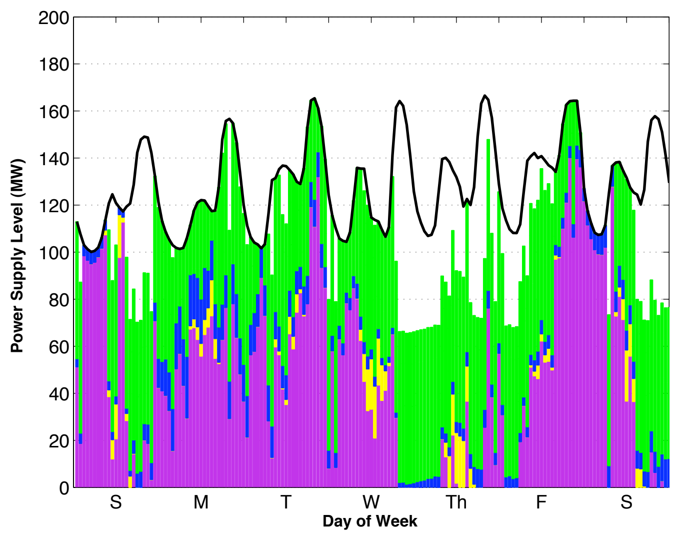


Figure 28: Winter power supply for December 14, 2008 through December 20, 2008. The black curve represents power demand.

Scenario Three: Net Zero Humboldt County

Another strategy to compensate for wind, solar, and ocean–wave intermittency is to use the transmission capacity in Humboldt County to import needed power and export surplus power. Humboldt County imports power now so this fits the status–quo well. The goal of this scenario, with power sources shown in Table 3, is to export as much power as we import: a net–zero Humboldt County.

Power Plant	Plant Type	Size (MW)
Fairhaven Power Company	Biomass	18MW
Humboldt Redwood Company	Biomass	32.5MW
Continental Resources Solutions Ultrapower 3	Biomass	13.8MW
Bear River Ridge (Shell)	Wind	140MW
Blue Lake PV Array	Solar	25MW
Redway PV Array	Solar	25MW
WaveConnect (PG&E)	Ocean–Wave	50MW
Transmission Lines	Transmission	70MW
		374.3MW

Table 3: Net Zero Humboldt County power supply sources, showing Actual and *Potential* generation facilities.

Using the same power generation described in the previous scenario along with transmission lines as shown in Table 3, a twenty–four hour visualization cycle for January 1, 2008 is shown in Figure 29. It appears in Figure 29 all demand is met, but from 7:00PM to 8:00PM, power demand is not quite met as can be seen in Figure 30(j) when a portion of the county turns black indicating power outage.

The visualization of the twenty–four hour cycle is shown in Figure 30. Each slice of time can be matched to the supplied power shown in Figure 29. Notice that the supplied power quantities do not match the geospatial layout in percentage of surface area covered. This is due to the power demand being set according to population density (see Figure

19 on page 30). A particularly clear example is 8:00AM where, according to Figure 30, biomass is powering one third of the county but the number of cells colored green in Figure 30(d) are very few. Most of the county appears to be powered by wind and transmission but the cells covered by these have low population density and therefore, low power demand.

The summer week run of July 1, 2008 through July 7, 2008 shown in Figure 31 appears to meet demand. The power supply levels for the peak demand period in winter, December 14, 2008 through December 20, 2008 are shown in Figure 32 where it is evident that 7% of the time, demand is not met. The winter week described contains the highest demand times of the entire year. Annually, with this set of power supplies, demand is not met only 0.97% of the time or 85 hours out of 8784 hours.

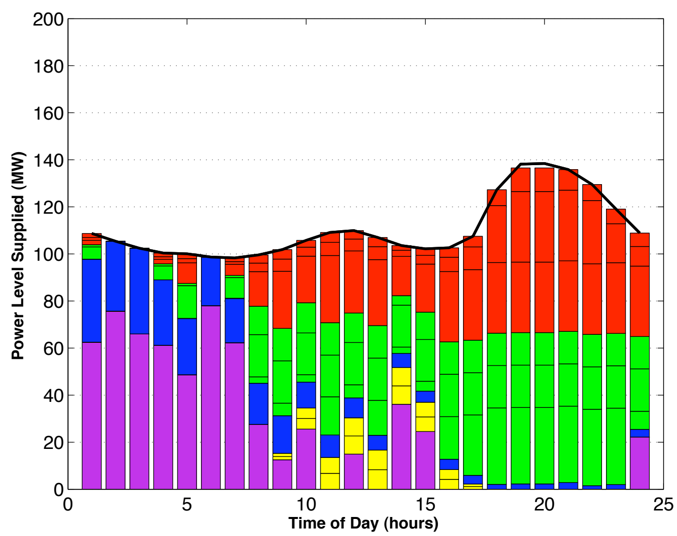
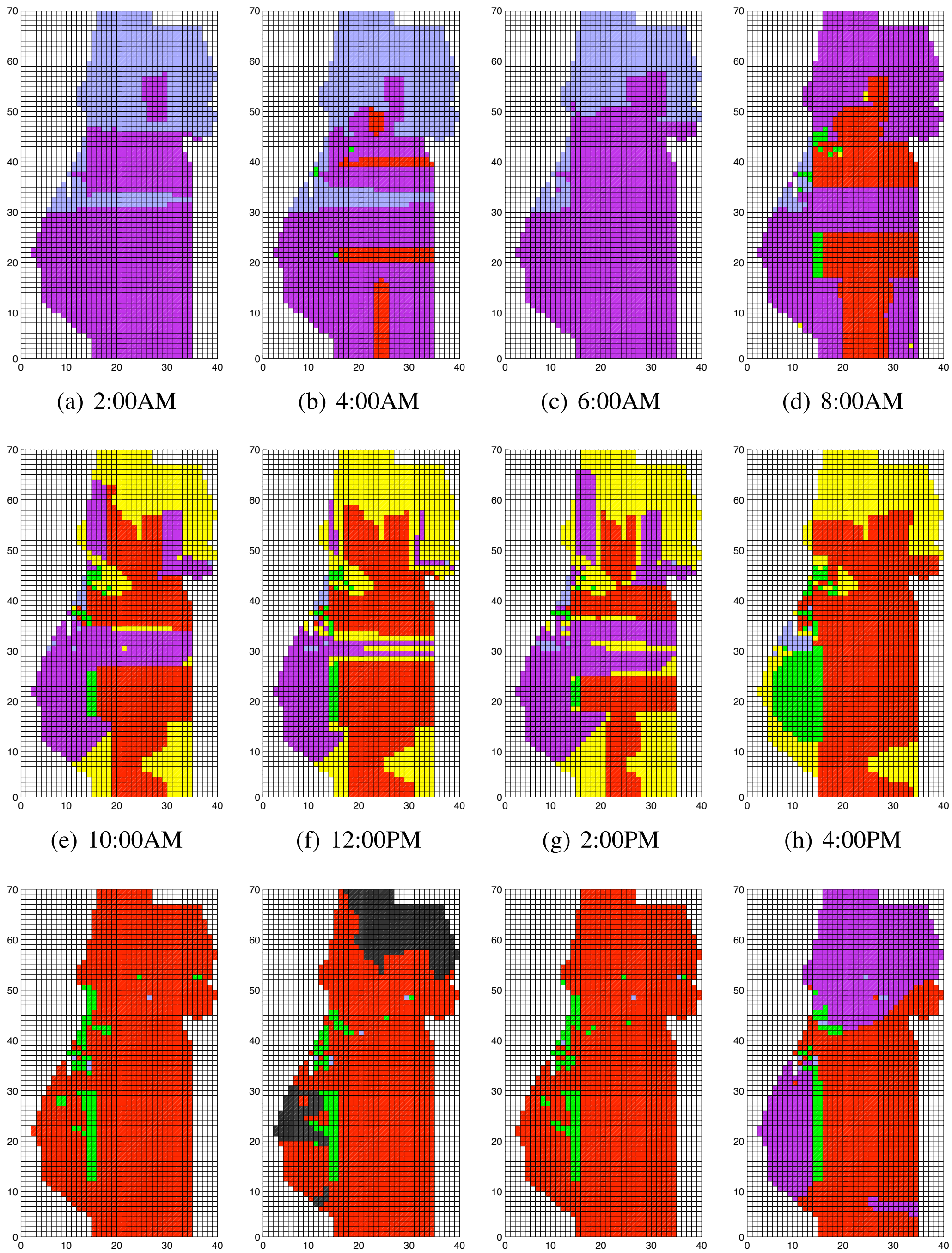


Figure 29: Power supplied for January 1, 2008 where purple is wind power, blue is wave, yellow is solar, green is biomass, and red is imported power via transmission lines. The black curve is power demand. Nearly all demand is met in this twenty–four hour section.

Since this scenario seeks for a net–zero Humboldt County, we will be relying on the transmission lines for import and export. In order to tell how effective this is, it is important to see the effects of powering the system without the transmission. A plot of the difference



(a) 2:00AM (b) 4:00AM (c) 6:00AM (d) 8:00AM

(e) 10:00AM (f) 12:00PM (g) 2:00PM (h) 4:00PM

(i) 6:00PM (j) 8:00PM (k) 10:00PM (l) 12:00AM

Figure 30: The geospatial power supplied on January 1, 2008. Notice that power is not met at 8:00PM. Each plot can corresponds to a column in Figure 29. Notice that power demand is dependent on population density and at 8:00PM, there is not enough power supplied so some of the county is blacked out.

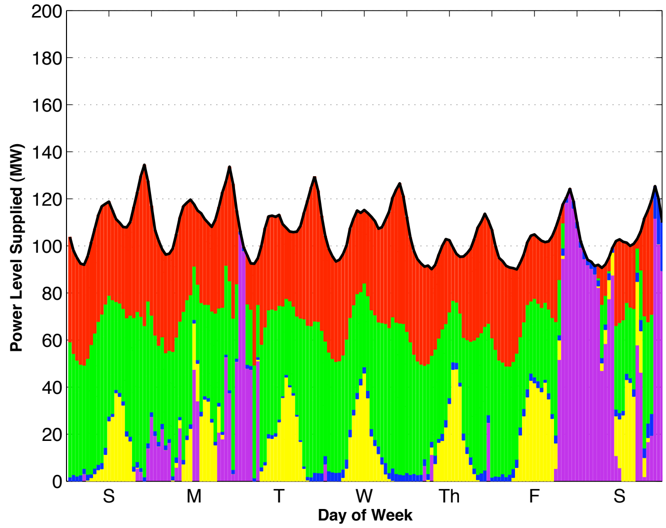


Figure 31: Power supplied for July 1, 2008 through July 7, 2008. The black curve is power demand which looks like it has been met the whole time.

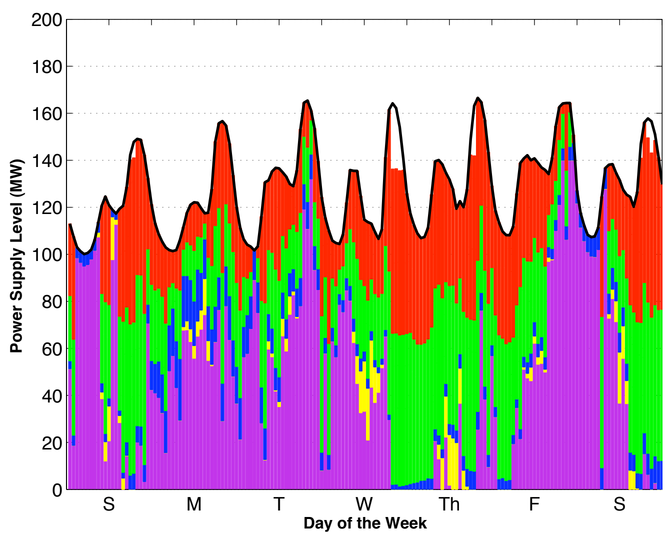


Figure 32: Power supplied for December 14, 2008 through December 20, 2008. Power demand is met most of the time but not quite all the time.

between supplied power (without transmission lines) and power demand is shown in Figure 33. The ±70MW is given as a horizontal dotted line so that the transmission import limit (+70MW) and export limit (-70MW) can clearly be seen. Another important dotted line is shown at +134.3MW denoting the maximum level at which turning down biomass power plants would be an effective way of not exceeding transmission export capacity.

Although we can tell that 70MW is not enough to meet demand 100% of the time nor to export all surplus power 100% of the time, Figure 33 is difficult to read. A cumulative sum of power deficits and surpluses in Figure 34(a) shows that Humboldt County would be in surplus the whole year.

A deficit–surplus duration plot for 2008 is shown in Figure 34(b). The duration plot shows the percentage of 2008 that power supply would be in deficit or surplus. Power demand cannot be met by importing power (is below -70MW) for only 0.97% or 85 hours of the year. Power generation exceeds that which can be exported (is above +70MW) 22.53% or 1,979 hours of the year. Since the biomass power generation can be increased on–demand to help meet loads, it can also be decreased on–demand to help not exceed export capacity of the county. Biomass capacity plus transmission capacity is shown on the plot at 134.3MW. When generation exceeds demand by more than the export capacity of 70MW, biomass generation can be turned down. If we include the ability to turn down biomass on–demand, then we have an energy surplus that we cannot export only 2.81% or 247 hours of the year.

The summer deficit and surplus plot, Figure 35(a), shows that the power deficits can be met with imported power 100% of the time. The export limit of +70MW is reached on at other end 7.74% of the time or 13 hours of the summer week. During these 13 hours, biomass power plant production could be reduced. The net energy supply for the summer week shown is -1,626 MWHrs meaning we would have imported 1,626 MWHrs more than we exported.

Winter power deficits and surpluses are not so easily met. According to Figure 35(b), the winter week suffers from a power deficit greater than the maximum transmission import capacity of 70MW 7.14% of the time or 12 hours of the week; a new strategy must be developed to cover the 10MW to 20MW needed in those times. Power supply is also far above the maximum export capacity of 70MW 10.71% of the time or 18 hours of the week. Similar to the summer week, biomass power can be generated on demand and reducing the supply would allow for maximum export without left–over unused energy. Low summer power demand in Humboldt County coincides well with less wind and calmer seas but with full sun to make up for it. High winter power demand coincides well with high winds and rough seas generating more power. Various options remain to help meet the times when demand exceeds both supply and import capacity. The net energy supply for the winter week is -258 MWHrs meaning we would have imported 258 MWHrs more than we exported.

Assuming we could import all needed energy in 2008, we would import 115.14GWHrs. Taking into account the limitations of the transmission infrastructure and the 0.97% of the time when we could not import enough energy, we would import 114.62GWHrs. If we could export all surplus energy, we would export 276.04GWHrs. If we again take into account the limitations of the transmission infrastructure, we would have been able to export only 205.59GWHrs. In either case, exported energy exceeds imported energy by a great deal making Humboldt County a net energy exporter.

To recap, the goal of this scenario was a net–zero Humboldt County. The results exceeded expectations. To reduce power exported, biomass plant capacities could be adjusted during off–peak times when additional transmission capacity is available for importing

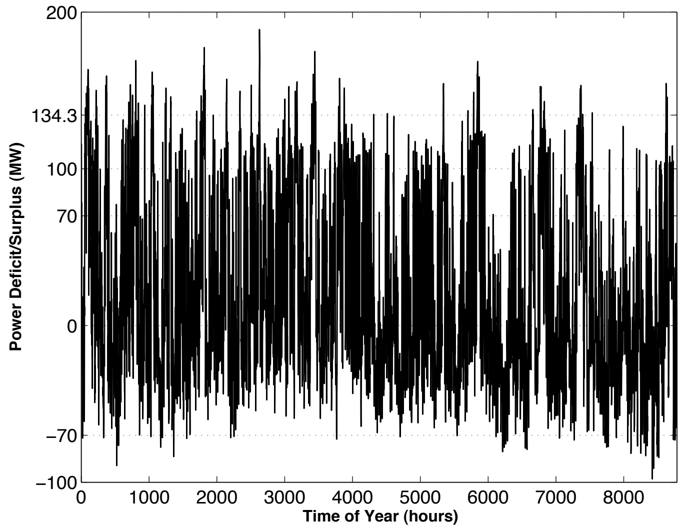
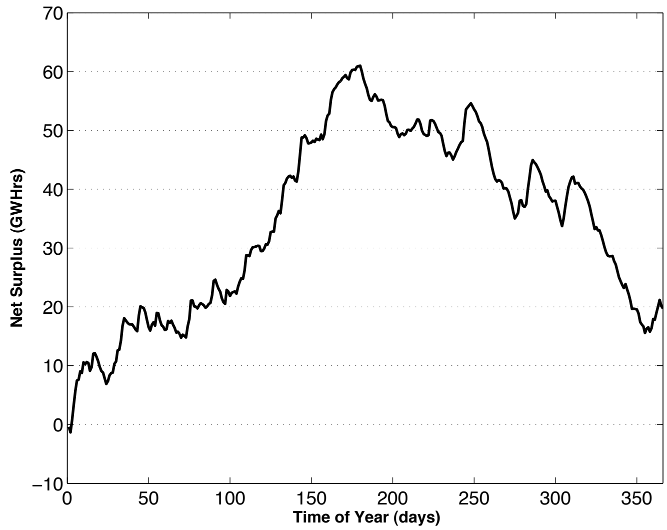
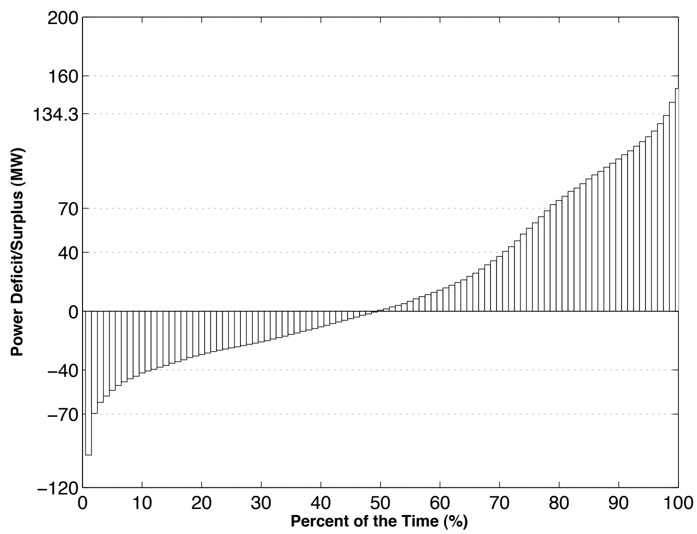


Figure 33: The difference between power supplied without transmission and total power demand year round in 2008. Notice ±70MW are shown as horizontal dotted lines showing the cutoff for imported and exported power.

power. Keeping biomass plants at full power on–peak while reducing production off–peak should reduce production while increasing profitability and bring the county closer to the net–zero goal.

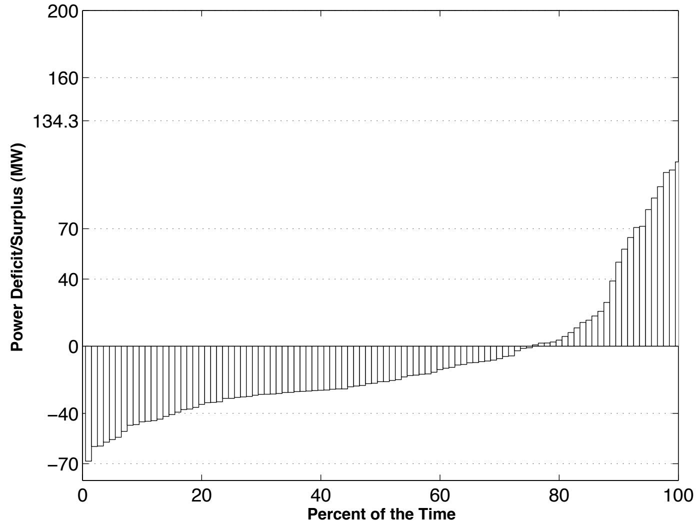


(a) Accumulated net surplus by day.

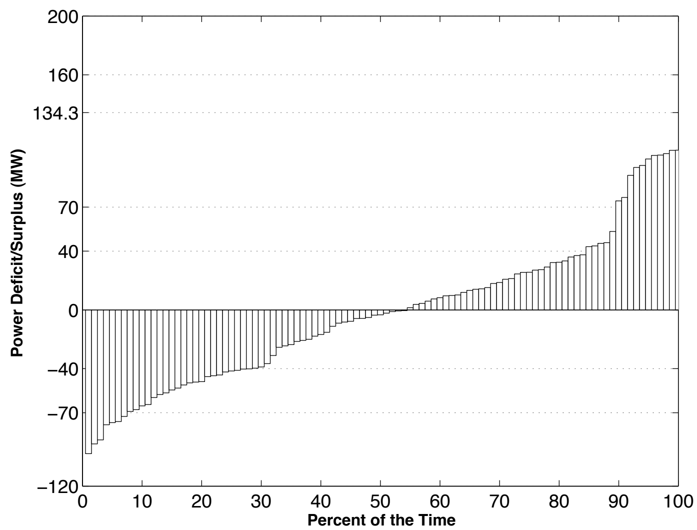


(b) A week in winter – December 14, 2008 through December 20, 2008.

Figure 34: The difference between power supplied only with renewable sources and total power demand year round in 2008. Important values are delineated on the vertical axis, namely the ±70MW showing the cutoff for imported and exported power. Another important number is 134.3MW which is the transmission capacity plus 100% of the biomass power generation.



(a) A week in summer – July 1, 2008 through July 7, 2008.



(b) A week in winter – December 14, 2008 through December 20, 2008.

Figure 35: The difference between power supply only with renewable sources and power demand. Power deficits and surpluses for the summer (a) and winter (b) show how often importing and exporting power would be necessary.

DISCUSSION

Numerous assumptions were required for completion of this model. Some assumptions were based on available data while others were process simplifications necessary to limit the scope of the investigation.

Demand

Power demand in this model is based on residential use. We distribute the entire load shape based on population density. Non–residential load likely peaks at different times than residential load. However, limited data was available on non–residential power use. Non–residential zoning could have been used to determine a non–residential demand density map. While we knew that non–residential demand accounted for 60% of annual demand, the hourly percentages were unknown. A non–residential demand density map might have allowed for more accurate geospatial power demand distributions, but the residential and non–residential load shapes would have been exactly 40% and 60% of the total load shape at all times, respectively. The more accurate geospatial distribution would have altered the visualization results by shuffling new demand into different cells of the model, but ultimately, the question of residential versus non–residential is not relevant to the scope of this investigation which used the total of both.

Supply

Biomass

Additional biomass generation was not considered. The current waste stream from lumber harvest is enough to supply the three biomass power plants discussed. Reducing forest fuel load through removal of dead biomass, while labor intensive, could add to available resources. Even without reducing forest fuel load, there may be enough waste from current lumber harvest to support added biomass power plant capacity.

Biomass power plant ability to ramp up and down was not taken into account. This would have required tracking previous and next hours of demand and supply instead of only the current hour and calculating how much biomass plants could be expected to ramp up or down to mitigate the quick changes in intermittent supplies. While biomass cannot be ramped up and down with infinite efficiency nor infinite speed, a more advanced power grid that includes both better weather forecasting and demand response might allow such challenges to be managed.

Wind

Capacity credits are assigned when estimating how much power a wind farm can be expected to compensate for. Capacity credits are calculated based on the intermittence of the supply and the effect it would have on total system reliability. Since this model does not consider system reliability, capacity credits are out scope. That said, the capacity credit described for the 140MW wind farm was 30%, meaning the wind farm would be expected to hold an annual average output of 42MW. With an annual average of 42MW, wind power would meet 37% of Humboldt County's needs, a 37% penetration. This is beyond the usual 20% threshold adopted by many wind energy associations (WEAs)(BWEA, 2009). Ways to mitigate high penetration of intermittent power sources are out of scope for this investigation. A more realistic assumption for wind power would limit penetration to 20%. This means the wind capacity credit could not exceed 22MW which, at 30% equates a maximum 75MW wind farm.

Another option would be to allow a maximum of 75MW wind generation to supply the county and use any power above that level to store energy as compressed air, hydrogen, or some other storage medium. The stored power could be reclaimed on demand with some predetermined percentage loss. With only 75MW of wind power generation, an immediate effect would be less power available in the winter. Even at a loss, the reclaimed energy on–demand might have allowed the county to meet 100% of demand year round depending on the size of the energy storage solution.

Solar

Solar power estimates were kept conservative in this model. This model focused on available beam and diffuse solar (global horizontal) insolation striking a surface parallel to the ground. In reality, nearly all solar PV power plants track the sun with at least one degree of freedom. That is, they track the azimuth angle or the seasonal change in angle of the sun. Some solar PV systems track the sun as it crosses the sky as well, known as dual–tracking systems. It is considered a trade–off to spend energy tracking the sun across the sky each day. The costs of including a dual–tracking system often outweigh the gains. Using direct normal insolation data would have greatly increased solar power generation numbers and been more accurate.

This model also focussed exclusively on solar PV power plants. Another option is a solar concentrating power plant which uses mirrors to concentrate solar insolation and generates power with a boiler. Modeling a solar concentrating power plant along side a solar PV plant with the 2008 data to see which one generates more power might prove useful. But solar concentrating power plants only work with beam radiation while solar PV plants work with both beam and diffuse sunlight. A comparison of energy generation with solar PV versus energy generation with a solar concentrating plant with the 2008 SoRMS data could address the question of which solar power source is a better option. A concentrating solar thermal power plant like those designed by BrightSource Energy (2009) might be effective in Humboldt County if constructed inland away from the fog and commonly overcast weather experienced on the coast. In such a scenario, it would be necessary to have data from the inland area since the solar monitoring station data used in this model came from the foggy overcast region of Humboldt County.

The original intent of this model was to distribute solar PV arrays on the rooftops of houses throughout Humboldt County. The primary obstacle to this calculation is the variability of solar insolation throughout the county. The power distribution side of the model made such a scenario difficult to model. One large benefit of such a model is that power demand, concentrated based on population density, would couple well with a power supply also concentrated based on population density.

Ocean–wave

Ocean–wave power has the least available data. The paper provided by von Jouanne (2004) was a life–line for this model. All companies contacted explained that their data was proprietary. Professor von Jouanne detailed a point source wave energy converter (WEC) they had tested. In their tests, they found that the direction the waves traveled had very little impact on the WEC's ability to operate. She went on to say that the efficiency, direction factor, and details of the WEC they tested were later incorporated into the AquaBuOY by Finavera which is now proprietary. Clearly this model would benefit from more accurate ocean–wave data and WEC frequency response curves, but there was little data available at the time.

Even though the wave data used for the ocean–wave power calculations was taken from a site many miles away, ocean–waves are caused by storms far out to sea, and waves measured miles apart often have the same characteristics (Stewart, 2008). With this in mind, it is likely that the timing was slightly off for each measurement since the wave needed to travel approximately 17 nautical miles to reach the WEC farm.

Transmission Lines

According to PG&E Account Executive Ivan Marraffo, the two 115kV transmission lines coming into Humboldt County are ultimately connected and have a maximum capacity of 70MW. The two 60kV transmission lines are used mostly for power distribution and to help move power should one of the larger lines have problems (Marruffo, 2009). So the transmission lines as modeled in this thesis do not hold to the current function of the lines. That said, a new power backbone was a prerequisite for this model. Also, eliminating the two 60kV transmission lines from the model but keeping the overall maximum power capacity at 70MW would only effect the geospatial visualization and not the power supply results.

The main flaw in the assumptions of this model was the "infinitely availability" of the grid. This model assumed the transmission lines coming into Humboldt County were always available for power exportation needs. This neglects the possibility that some of the transmission capacity may be in use to distribute power locally. For example, the 115kV line traveling near Highway 299 was modeled as a 30MW power supply source. It would be difficult to export 30MW on that line if 10MW of the transmission capacity were being used to power Blue Lake and Willow Creek. It might make sense, therefore, to place power generation facilities at the edges of Humboldt County. But again, this model assumed a new transmission grid backbone. A more detailed analysis of the current transmission availability for import and export of power coupled with this model would be an appropriate followup investigation.

Energy Storage

Lack of sufficient energy storage solutions for large scale power generation is the bane of intermittent power sources. Since there are no large energy storage solutions, all power demand must be generated as it is used (Casazza and Delea, 2003). Pumped storage, where water is pumped into an upper reservoir and then drained through hydroelectric generators when needed, is one option for storing energy (FERC, 2009). Another option is to use electricity to generate and store Hydrogen gas, H_2, then use a Hydrogen power plant to generate electricity on–demand. The energy loss from storing energy as Hydrogen can be included in the overall efficiency of the operation. Generating power on–demand allows for smoothing of some intermittence experienced in solar, ocean–wave, and wind power plants. In this model, energy storage could eliminate the need to import power altogether. However, to simplify the project and keep it within a reasonable scope, power storage solutions were not included.

Algorithms

The process of deciding which cell receives power from which power supply went through numerous revisions. I tried to write an optimization routine minimizing straight line distance from each cell to its power source but quickly realized such a routine represented a thesis on its own. Likewise, powering one cell from more than one power source required too much work.

With optimization out of the picture, looping through the cells was the first task. Looping through from north to south or east to west would leave the calculations too dependent on which corner they started in. Instead, the cells are sorted by distance to their nearest power source or distance to their nearest available power source or distance, etc. Distributing power right away to the nearest available intermittent power source produced odd results where some cells that were right next to a biomass plant might end up powered by wind half way across the map simply because their power source got used up before they were assigned. This lead to assigning all cells to their nearest source first and dealing with the deficits caused by it after. The ultimate goal remained to minimize distance, so each loop was run based on distance. While the current model may not be optimal, it provides a good first look at smart grid obstacles to be considered in a full scale GEP.

Sensitivity Analysis

Overall, increasing any of the intermittent power supplies would not help meet power demand when all three sources were not producing. It was the intent of this model to stay on the realistic side of power plant sizes and to investigate the issues of power supply and distribution of multiple simultaneous renewable power sources. The ocean–wave power plant could have been increased to a 500MW farm. At that size, even when wave power was at its minimum supply of 0.8%, that would be 4MW. At peak power production, the ocean–wave power plant would be outputting 500MW which would have to be used for something. While increasing solar and wind power plant sizes would increase production, both solar and wind have times of zero power production while ocean–waves keep coming even if they are very small.

With power plants of this size and the use of energy storage, we could look at meeting not only electricity demand but transportation and heating as well. It would make more sense in such a scenario to use the EnergyPLAN software developed by Lund et al. (2004) which would allow for a financial analysis of the possibility.

CONCLUSION

This investigation addressed the electricity generation capacity of four Humboldt County renewable power sources: wind, solar, ocean–wave, and biomass. Three scenarios were tested: current power; only–renewable; and net–zero. A detailed transmission and distribution model demonstrated that meeting 100% of power demand in Humboldt County from renewable sources at the time of the demand is not feasible due primarily to:

1. The wind, solar, and ocean–wave sources are intermittent. Even if the power supplies were multiplied 10–fold, the three intermittent sources often jointly produce little or no power. When the three intermittent sources produce no power, biomass must be used to compensate.

2. Current biomass power plants, using the byproduct of the local forest products industry, is insufficient to fill the power gaps created by the intermittent renewable sources.

3. Energy storage of generation by intermittent sources in times of surplus is not evaluated in this model.

The best path to increased use of renewable in Humboldt County is increased transmission capacity. Given power plant sizes from the Net–Zero Humboldt County scenario, an increase in transmission capacity of 30MW would allow Humboldt County to meet increased power demand solely with imported and biomass power during the 0.97% of the year it is necessary. Increased transmission capacity might encourage companies like Shell WindEnergy Inc. to construct larg renewable power plants in Humboldt County since they would be able to export their power when demand is already met through other means. Another solution would be to store the energy in hydrogen form. Although there is a net energy loss when using electricity to generate hydrogen and then using hydrogen to generate electricity, some efficiency is better than zero.

Regardless of the solution, power generation in Humboldt County and throughout the world is already shifting to the soft energy path described by Lovins (1976). If and when nuclear fusion is viable, even imported power from the central valley, with line loss and the carbon footprint of large scale transmission, may be cheaper and cleaner than local biomass generation.

FUTURE WORK

The visualizations show power supply in a constant flux. These dynamics are a glimpse at what smart power grids will need to manage. Smart grid technologies are quickly permeating the market. Smart metering provides better power usage data to power companies, who can then use the data to design comprehensive demand response programs, and to educate the public about prudent power use.

In the simulations, demand was dispersed based on population density, which implies that 100% of demand is residential. In reality, only 40% of demand in Humboldt County is residential. Accurate location targeting of commercial power demands would increase general accuracy of the simulation model and would allow for further investigation into per capita energy consumption in transportation and heating. For example, if the county was running on the system described in the net–zero scenario, generating over 100GWHrs per year in excess of needed electricity, how much of county transportation needs could be covered by this surplus?

As of 2003, Humboldt County had the highest residential solar installed wattage per capita of all counties in California (Zoellick, 2005). The solar power component of the model could be extended to small solar arrays on the roofs of Humboldt County residences, with variations in solar power generation capacity calculated by population density and insolation potential. Thus, instead of placing two 25MW solar plants, 50MW of solar generating capacity could be spread across residential locations. The resulting dispersed supply would have different dynamics than two large plants.

The ocean–wave power plant assumed in this model was of modest size, especially given the available area the ocean has to offer. This model also assumed a linearly aligned wave farm so that no buoys would fall in the shadow of one another. Better numbers on the efficiency loss of building WEC farms in arrays could lead to more productive use of seascape.

Wind power estimates would benefit from data local to the site. Also, since wind does not blow the same across the whole county, wind farms could be located in more regions. It would be interesting to compute wind data from multiple locations to see if separate wind farms would compensate for each other's intermittence.

Biomass power production was simplified in this model. Expanding the model to compensate for the rates at which local biomass plants can ramp up and down would be helpful in determining feasibility of renewable energy penetration.

Wholesale power prices for importing power during peak and off–peak demand times may fluctuate. These changes could be exploited to determine when to generate power locally with biomass and when to import power.

A feasibility study of the costs involved in adding transmission capacity to the county is warranted. It is likely that local power companies have already researched building additional transmission lines.

Smart meters, which allow power companies to constantly monitor their customer power demands, are being installed regularly. PG&E's SmartMeter™ program is the largest in the United States with over two million smart meters installed (PG&E, 2009b). Regular meters are read by hand once each month to determine power usage. The rate for the month is determined by how much was used but not when it was used. Different amounts of use fall into different rate brackets. Imagine if PG&E could change the price of power based on time of use. Taking this concept a step further, they could also change the price of power based on how much renewable energy was being supplied. For example, imagine a weather forecast that includes mention of cheap electricity due to a windy week-end. Power price could fluctuate not only based upon how much was being used at once, but upon how much was being generated.

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APPENDIX A: Code

The code is mainly for reference but if running it was desired, contacting the author would be the best way to get the rest of the data needed. The “gep” prefix on each program stands for Generation Expansion Plan (GEP). A GEP is a ten or twenty year plan laid out by a power company showing the best course of action for meeting future energy needs. This thesis describes possible end scenarios for a GEP in Humboldt County.

Code File	Description	Page
gepVariables.m	variable declarations	68
gepSupplyData.m	loads and calculates supply data for each source	69
gepSupplies.m	reads the supply data provided by gepSupplyData.m into separate layers representing the location of each power source	77
gepDemandData.m	loads the load shape file and extracts the current demand	78
gepDemand.m	applies the demand density map to the demand data provided by gepDemandData.m	79
gepIndeces.m	calculates the distance from each cell to all available power sources	80
gepDistSteadyState.m	distributes power from sources to cells, this is the heart of the geospatial simulation	82
gepWrapper.m	the wrapper function that runs everything	90
gepPlot.m	generates various plots	92
gepColormap.m	generates needed colormaps for gepPlot.m	96

Table 4: Matlab Code.

This code was written using MATLAB R2008b Student Version for Mac OS X. The model was run on a MacBook with an Intel Core II Duo processor running Mac OS 10.5.6. There may be adjustments necessary to the code in order to run it on other systems.

Variables that might need adjusting are basic map layout variables in *gepVariables.m*, supply data locations and amounts within *gepSupplyData.m*, and the value of the variable "debug" in *gepWrapper.m* which controls movie creation (debug=1) or figure creation (debug=2).

The main wrapper function is useful when creating movies of short periods of time (1-200 hours in the model) or multiple figures of consecutive hours in short periods of time (1-24 hours in the model). To examine the year as a whole, the function "sensitivityAnalysis.m" can be run to load annual available power for each supply source and power demand. All code was written for optimal readability and not for speed. Running the main wrapper function for more than 200 hours often froze up machines, hence the recommendation to use the wrapper function for short runs.

A typical 24 hour run of *gepWrapper.m* might begin with

```
[powerSupplyStats,powerDemandStats,hourlyDemand]=gepWrapper([1,1,1],24,1);
```

which will run the model using the first scenario for 24 hours beginning January 1, 2008 at 1:00AM. Running *gepPlot.m* with the command `gepPlot(4,powerDemandStats);` will generate figures like those seen in the analysis section for the current power system.

Writing a complete manual for this code was not considered for this thesis. Please contact me if you would like more information.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepVariables.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% Define constants
%
% INPUTS: NONE
%
% OUTPUTS:
% humWidth - the width of humboldt county in miles
% humHeight - the heigth of humboldt county in miles
% boxSize - the length of one cell in miles, used in distance calcula-
tions
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Define Sizing Variables
function [humWidth,humHeight,boxSize]=gepVariables()

humWidth=40; % County is approximately 1.5*40=60 miles wide
humHeight=70; % County is appromixately 1.5*70=105 miles tall

boxSize = 1.5; % 1.5 miles on a side for distance calculations
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepSupplyData.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% Load and calculate supply data based on indicated scenario
%
% INPUTS:
% gepTime - [month,day,hour] - time to retrieve data for
%
% OUTPUTS:
% supplyData - a matrix of power density for each power.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Power Source Index:
% 0 = biomass
% 1 = wind
% 2 = solar
% 3 = wave
% 4 = transmission
% 5 = natural gas
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [supplyData,supplyRegions]=gepSupplyData(gepTime)
%% Initialize gepTime if no inputs
global scenario;
if(nargin==0)
    gepTime=[1,1,1];
end

%% Convert gepTime
% convert gepTime into a single number which represents the number of
hours progressed
monthDays=[31,28,31,30,31,30,31,31,30,31,30,31];
linearTime=(sum(monthDays(1:(gepTime(1)-1)))+gepTime(2)-1)*24+gepTime(3
);

%% DESIGNATE ACTIVE SOURCES BASED ON SCENARIO
% 1 = current power system in Humboldt County
% 2 = renewables only (solar, wave, biomass, wind)
% 3 = net-zero Humboldt (renewables + transmission)
%% SCENARIO SETUP
if(scenario==1)
    transmissionCapacity=0.75; % 75 percent transmission capacity
```

```
    biomassCapacity=0.75; % 75 percent biomass capacity
    fossilCapacity=0.70; % max 70 percent fossil fuel plant capacity
    windShell=0;
    solarBlueLake=0;
    solarRedway=0;
    wavePGE=0;
    biomassPalco=1;
    biomassFairhaven=1;
    biomassUltrapower=0;
    transmissionNE=1;
    transmissionSE=1;
    transmissionS=1;
    transmissionN=1;
    naturalgasPGE=1;
elseif(scenario==2)
    transmissionCapacity=1; % 100 percent transmission capacity max
    biomassCapacity=1; % 100 percent biomass plant capacity max
    windShell=1;
    solarBlueLake=1;
    solarRedway=1;
    wavePGE=1;
    biomassPalco=1;
    biomassFairhaven=1;
    biomassUltrapower=1;
    transmissionNE=0;
    transmissionSE=0;
    transmissionS=0;
    transmissionN=0;
    naturalgasPGE=0;
elseif(scenario==3)
    transmissionCapacity=1; % 100 percent transmission capacity max
    biomassCapacity=1; % 100 percent biomass plant capacity max
    windShell=1;
    solarBlueLake=1;
    solarRedway=1;
    wavePGE=1;
    biomassPalco=1;
    biomassFairhaven=1;
    biomassUltrapower=1;
    transmissionNE=1;
    transmissionSE=1;
    transmissionS=1;
    transmissionN=1;
    naturalgasPGE=0;
end

regionCount=0; % dynamic region selection/allocation
```

```
%% windShell SETUP
if(windShell==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[5,9,23,24,1,12,21];

windRegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(regionCoun
t+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regionCount+1,
3)+1);
    % load windpower.mat data - hourly windspeed
    load -mat windpower.mat; % windpower
    % need to compensate for 80m elevation change since the tower is
80m tall
    % windspeed for 80m is approx 1.6333 times the speed of 20m accord-
ing to maps
    % using firstlook.3tiergroup.com
    windSpeed=windpower(linearTime)*1.6333;
    % Vestas V90 2MW Power Curve:
    % 0MW for V < 4m/s
    % (2000*V/8 - 1000)MW for 4m/s <= V <= 12m/s
    % 2000MW for 12m/s < V <= 25m/s
    % 0MW for 25m/s < V
    if(windSpeed<4)
        V90Power=0;
    elseif(4<=windSpeed<=12)
        V90Power=(2000*windSpeed/8-1000);
    elseif(12<windSpeed<=25)
        V90Power=2000;
    else
        V90Power=0;
    end
    % Shell Wind - assumes 70 2MW Turbines
    % divide by region size to distribute wind power production
    % evenly throughout the region
    windDensity=V90Power*70/windRegionSize;
    supplyData(regionCount+1,1)=windDensity;
    regionCount=regionCount+1;
end

%% solarBlueLake SETUP
if(solarBlueLake==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[19,19,42,42,2,19,42];

solarBlueLakeRegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(r
egionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regio
nCount+1,3)+1);
    % load solarpower.mat data - hourly solar insolation (W/m^2)
    load -mat solarpower.mat;
```

```
    % panel effeciency assumed to be 10%
    % 250,000 square meters of panels (max 25MW/box)
    % 1000W in 1kW
    solarDensity=solarpower(linearTime)*0.10*250000*0.001;
    supplyData(regionCount+1,1)=solarDensity;
    regionCount=regionCount+1;
end

%% solarRedway SETUP
if(solarRedway==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[25,25,7,7,2,25,7];

solarRedwayRegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(reg
ionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regionC
ount+1,3)+1);
    % load solarpower.mat data - hourly solar insolation (W/m^2)
    load -mat solarpower.mat;
    % panel effeciency assumed to be 10%
    % 250,000 square meters of panels (max 25MW/box)
    % 1000W in 1kW
    solarDensity=solarpower(linearTime)*0.10*250000*0.001;
    supplyData(regionCount+1,1)=solarDensity;
    regionCount=regionCount+1;
end

%% wavePGE SETUP
if(wavePGE==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[10,10,39,42,3,11,39];

wavePGERegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(regionC
ount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regionCount
+1,3)+1);
    % load wavepower.mat data - hourly waveheight and waveperiod
    load -mat wavepower.mat;
    height=waveheight(linearTime);
    period=waveperiod(linearTime);
    % From Thorpe 1999 (pg 24) - Eqn 2.6
    % --> Power(kW/m)=0.49*H^2*T
    % From PG&E WaveConnect Plan
    % --> Approx 25MW per square mile
    % From Prof. von Jouanne 2004
    % --> 20m incident, 0.9 directional coefficient, 30% eff of extrac-
tion
    % --> WECPower(kW)=Power*20*0.9*0.3
    % max of 500kW single power source
    Power=0.49*height^2*period;
```

```
    WECPower=Power*20*0.9*0.3;
    if(WECPower>500)
        WECPower=500;
    end
    buoyDensity=16; % buoys per linear mile - this allows 1600m/16=100m
per buoy
    wavePowerPerCell=WECPower*buoyDensity*1.5; % grid boxes are 1.5
miles on a side
    waveDensity=wavePowerPerCell;
    supplyData(regionCount+1,1)=waveDensity;
    regionCount=regionCount+1;
end

%% biomassPalco SETUP
if(biomassPalco==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[15,15,21,21,0,15,21];

biomassPalcoRegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(re
gionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(region
Count+1,3)+1);
    % biomass power is assumed to remain constant for each supply
    % make certain each region size is 1x1
    % biomass power is assumed constant based on capacity set at top of
this file
    biomassPalcoDensity=32500*biomassCapacity;
    supplyData(regionCount+1,1)=biomassPalcoDensity;
    regionCount=regionCount+1;
end

%% biomassFairhaven SETUP
if(biomassFairhaven==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[11,11,38,38,0,11,38]; % BIOMASS %
FAIRHAVEN %

biomassFairhavenRegionSize=(supplyRegions(regionCount+1,2)-supplyRegion
s(regionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(re
gionCount+1,3)+1);
    % biomass power is assumed to remain constant for each supply
    % make certain each region size is 1x1
    % biomass power is assumed constant based on capacity set at top of
this file
    biomassFairhavenDensity=18000*biomassCapacity;
    supplyData(regionCount+1,1)=biomassFairhavenDensity;
    regionCount=regionCount+1;
end
```

```
%% biomassUltrapower SETUP
if(biomassUltrapower==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[18,18,42,42,0,18,42];

biomassUltrapowerRegionSize=(supplyRegions(regionCount+1,2)-supplyRegio
ns(regionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(r
egionCount+1,3)+1);
    % biomass power is assumed to remain constant for each supply
    % make certain each region size is 1x1
    % biomass power is assumed constant based on capacity set at top of
this file
    biomassUltrapowerDensity=13800*biomassCapacity;
    supplyData(regionCount+1,1)=biomassUltrapowerDensity;
    regionCount=regionCount+1;
end


%% transmissionNE SETUP
% 30MW transmission line entering from the east along Hwy 299
if(transmissionNE==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[16,34,39,39,4,25,39];

transmissionNERegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(
regionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regi
onCount+1,3)+1);
    % transmission lines are assumed to remain constant for each supply
    % make sure to divide by region size
    % transmission line capacity is constant based on capacity set at
top of this file
    transmissionNEDensity=30000/transmissionNERegionSize;

supplyData(regionCount+1,1)=transmissionNEDensity*transmissionCapacity;
    regionCount=regionCount+1;
end

%% transmissionSE SETUP
% 30MW transmission line entering from the east along Hwy 36
if(transmissionSE==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[16,34,21,21,4,25,21];

transmissionSERegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(
regionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regi
onCount+1,3)+1);
    % transmission lines are assumed to remain constant for each supply
    % make sure to divide by region size
```

```
    % transmission line capacity is constant based on capacity set at
top of this file
    transmissionSEDensity=30000/transmissionSERegionSize;

supplyData(regionCount+1,1)=transmissionSEDensity*transmissionCapacity;
    regionCount=regionCount+1;
end


%% transmissionS SETUP
% 5MW transmission line entering from the south on Hwy 101
if(transmissionS==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[24,24,1,15,4,24,7];

transmissionSRegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(r
egionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regio
nCount+1,3)+1);
    % transmission lines are assumed to remain constant for each supply
    % make sure to divide by region size
    % transmission line capacity is constant based on capacity set at
top of this file
    transmissionSDensity=5000/transmissionSRegionSize;

supplyData(regionCount+1,1)=transmissionSDensity*transmissionCapacity;
    regionCount=regionCount+1;
end

%% transmissionN SETUP
% 5MW transmission line entering from the northeast - Trinity County
if(transmissionN==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[23,23,46,69,4,23,58];

transmissionNRegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(r
egionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regio
nCount+1,3)+1);
    % transmission lines are assumed to remain constant for each supply
    % make sure to divide by region size
    % transmission line capacity is constant based on capacity set at
top of this file
    transmissionNDensity=5000/transmissionNRegionSize;

supplyData(regionCount+1,1)=transmissionNDensity*transmissionCapacity;
    regionCount=regionCount+1;
end

%% naturalgasPGE SETUP
```

```
% Humboldt Bay Power Plant by PG&E
% 135MW Capacity
if(naturalgasPGE==1)
    % Region mapping - [x1,x2,y1,y2,index,center_x,center_y]
    supplyRegions(regionCount+1,:)=[11,11,34,34,5,11,34];

naturalgasPGERegionSize=(supplyRegions(regionCount+1,2)-supplyRegions(r
egionCount+1,1)+1).*(supplyRegions(regionCount+1,4)-supplyRegions(regio
nCount+1,3)+1);
    % natural gas plant capacity remains constant
    % make certain each region size is 1x1
    naturalgasPGEDensity=135000*fossilCapacity;
    supplyData(regionCount+1,1)=naturalgasPGEDensity;
    regionCount=regionCount+1;
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepSupplies.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% Draw a grid to represent Humboldt County
% Create regions within their own layers for WIND, SOLAR, BIOMASS, WAVE
%
% INPUTS:
% gepTime - [month,day,hour] - time to retrieve data for
%
% OUTPUTS:
% supplyMap - a matrix depicting supply of humboldt county
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [supplyMap]=gepSupplies(gepTime)
%% If No Inputs, Load Defaults
if nargin==0
    gepTime=[1,1,1];
end
% load power supply density per cell and location of cells
[supplyData,supplyRegions]=gepSupplyData(gepTime);

%% Load variables from variable file gepVariables.m
[humWidth,humHeight]=gepVariables();
numberOfRegions=size(supplyRegions,[1]);

%% Initialize a density map storage variable to store all maps
% load order is dependent on the scenario setting gepSupplyData.m
supplyMap=zeros(humWidth,humHeight,numberOfRegions); % create sum layer

%% SUPPLY MAPS %%%%%%%%%%%%
% one layer for each power supply
% each cell on that layer where the supply is located is set to density
% calculated within gepSupplyData.m
for(i=1:humWidth)
    for(j=1:humHeight)
        for(k=1:numberOfRegions)
            if((i>=supplyRegions(k,1) && i<=supplyRegions(k,2)) &&
(j>=supplyRegions(k,3) && j<=supplyRegions(k,4)))
                supplyMap(i,j,k)=supplyData(k);
            end
        end
    end
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepDemandData.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% load the loadshape file provided by PG&E
% return the demand for the specified gepTime
%
% INPUTS:
% gepTime - [month,day,hour] - time to retrieve data for
%
% OUTPUTS:
% currentDemand - total demand for the county at given time
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [currentDemand]=gepDemandData(gepTime)
if nargin==0
    gepTime=[1,1,1];
end

%% Load Demand Data
% this loads the 1x8784 loadshape
% hourly power demand in Humboldt County for 2008
load -mat loadshape.mat;

%% Convert Time
% convert gepTime into a single number which represents the number of
hours progressed
monthDays=[31,28,31,30,31,30,31,31,30,31,30,31];
linearTime=(sum(monthDays(1:(gepTime(1)-1)))+gepTime(2)-1)*24+gepTime(3
);

% get the current demand
currentDemand=loadshape(linearTime);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepDemand.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% load the population density map for Humboldt County
% create and return the demand map for the specified time
%
% INPUTS:
% gepTime - [month,day,hour] - time to retrieve data for
%
% OUTPUTS:
% demandMap - array of demand for Humboldt County
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [demandMap]=gepDemand(gepTime)
%% If No Inputs, Load Defaults
if nargin==0
    gepTime=[1,1,1];
end

totalDemand=gepDemandData(gepTime);

%% Load Population Density Map
load -mat popdensity.mat % variable popDensity

%% Populate Demand Map
% note multiply by 1000 to convert from MW to kW
demandMap = popDensity*totalDemand*1000;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepIndeces.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% Calculate distance from each cell to each power source
% Sort distances in order from nearest to furthest
%
% INPUTS: NONE
%
% OUTPUTS:
% closestPower - matrix describing which power is closest for each zone
% closestPower(i,j,k) = k-th closest power to cell(i,j)
%
% distancePower - matrix showing distance from each zone to each power
% distancePower(i,j,k) = distance to k-th supply from cell(i,j)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [closestPower, distancePower]=gepIndeces()
% Load supply source coordinates, supplyRegions is scenario dependent
[supplyData,supplyRegions]=gepSupplyData();

% Load variables from variable file gepVariables.m
[humWidth,humHeight,boxSize]=gepVariables();

% setting up for dynamically allowing n regions
numberOfRegions = size(supplyRegions,1);

%% ZONE DISTANCES
% Create zoneDistances Matrix
zoneDistances=zeros(humWidth,humHeight,numberOfRegions);
% find the distance from each cell to each power source
for(k=1:numberOfRegions)
    for(i=1:humWidth)
        for(j=1:humHeight)
            % if source is a Transmission Line, use entire length in-
stead
            % of a central point to calculate distance
            if(supplyRegions(k,5)==4) % if it's a transmission line
                if(supplyRegions(k,1)<=i && i<=supplyRegions(k,2))
                    Leg1 = 0;
                else
                    Leg1 =
boxSize*min(abs(i-supplyRegions(k,1)),abs(i-supplyRegions(k,2)));
                end
```

```
                if(supplyRegions(k,3)<=j && j<=supplyRegions(k,4))
                    Leg2 = 0;
                else
                    Leg2 =
boxSize*min(abs(j-supplyRegions(k,3)),abs(j-supplyRegions(k,4)));
                end
            % All other sources have a set central source location
            % Distance calculated using pythagoreans theorem
            else
                Leg1 = abs(boxSize*(i-supplyRegions(k,6)));
                Leg2 = abs(boxSize*(j-supplyRegions(k,7)));
            end
            zoneDistances(i,j,k)=sqrt((Leg1^2)+(Leg2^2));
        end
    end
end


%% CLOSEST POWER SUPPLY
% Create Index
% closestPower(i,j,k) = k-th closest supply to cell(i,j)
% distancePower(i,j,k) = distance to k-th supply from cell(i,j)
closestPower=zeros(humWidth,humHeight,numberOfRegions);
distancePower=zeros(humWidth,humHeight,numberOfRegions);

tempX=zeros(2,numberOfRegions); % temporary array for use
for(i=1:humWidth)
    for(j=1:humHeight)
        tempX(1,:)=[1:numberOfRegions];
        tempX(2,:)=zoneDistances(i,j,:);
        sortedX=sortrows(tempX',[2])'; % sort by distance
        closestPower(i,j,:)=sortedX(1,:); % store closest supplies
        distancePower(i,j,:)=sortedX(2,:); % store distance maps to
1st, 2nd, ..., nth furthest
    end
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepDistSteadyState.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% distribute power from sources to cells countywide so that:
% (1) all cells are powered if possible
% (2) intermittent (non-dispatchable) power supplies are exhausted
% (3) no power source returns in deficit
%
% INPUTS:
% demandMap - [40x70] power demand in each cell
% supplyMap - [40x70x(NumberOfSupplies)] power supply available
%
% OUTPUTS:
% newPoweredUp - [40x70x(NumberOfSupplies+1)] matrix showing which
cells
%                 got their power from which sources
% powerStatistics - total power generated by each source, total power
%                    supplied to a load by each source
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% FUNCTION DECLARATION
function
[newPoweredUp,powerStatistics]=gepDistSteadyState(demandMap,supplyMap)
%% Load gepVariables
[humWidth,humHeight]=gepVariables();

%% Load used data
[supplyData,supplyRegions]=gepSupplyData(); %supplyRegions is scenario
independent
sourceCount=size(supplyRegions,1);
[closestPower, distancePower]=gepIndeces();

%% Power Source Totals
powerSupplyPerSource=zeros(1,sourceCount); % initialize supply totals
powerSupplyPerSource(:)=sum(sum(supplyMap)); % 1xn - where n=number of
sources
powerDemandTotal=sum(sum(demandMap)); % 1x1 demand total

%% FIRST %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Return all zones to their closest source. %
%-------------------------------------------%
% 1. List coordinates for all zones.
[resetX, resetY]=find(demandMap);
```

```
% 2. Initialize poweredUp array to track which zone is powered
%    by which supply. Note additional slot is for blacked out zones
poweredUp=zeros(humWidth,humHeight,sourceCount+1);
% 3. Cycle through the list of all zones. For each zone, designate its
%    power source as the closest available. This may create or exacer-
bate some
%    deficits for some regions but these will be fixed in the following
loops.
for(i=1:size(resetX))
    % a. find nearest power source for each zone (resetX(i),resetY(i))
    powerSource=closestPower(resetX(i),resetY(i),1);
    % b. power the zone to the nearest power source.
    %    note: power demands are subtracted after this loop
    poweredUp(resetX(i),resetY(i),powerSource)=1;
end
%-----------%
% END FIRST %
%%%%%%%%%%%%%

%% FIRST- Totals Between -SECOND
powerDemandPerSource=zeros(1,sourceCount); % 1xn - initalize demand to-
tals
for(k=1:sourceCount)
    powerDemandPerSource(k)=sum(sum(poweredUp(:,:,k).*demandMap(:,:)));
end
% powerState is remaining supply (or deficit) for each source
powerState=(powerSupplyPerSource-powerDemandPerSource);
powerState=[powerState,0]; % add blacked-out spot

%% SECOND %%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Redistribute the zones in deficit. %
%------------------------------------%
% 1. Identify power sources that have deficits.
[defSources]=find((powerState)<0);
[availSources]=find((powerState)>0);
% 2. get (x,y,power,source,distance) for each zone on a deficit source
m=0;
for(i=1:length(defSources))
    % find coordinates and power demand
    % then put them in an array with the source index

[defX,defY,defPower]=find(poweredUp(:,:,defSources(i)).*demandMap(:,:))
;

defArray=[defX,defY,defPower,defSources(i)*ones(length(defPower),1)];
    % lookup the distance from each zone to the source
    for(j=1:length(defPower))
```

```
defSourceIndex=find(closestPower(defX(j),defY(j),:)==defSources(i));
        distDef(j)=distancePower(defX(j),defY(j),defSourceIndex);
    end
    % put the data into one package
    defArrayPlus=horzcat(defArray,distDef');
    if(m==0)
        defArrayWhole=defArrayPlus;
    else
        defArrayWhole=[defArrayWhole;defArrayPlus];
    end
    m=m+1;
    clear defArray distDef;
end
% 3. sort the results by power (largest to smallest)
sortedDefArray=sortrows(defArrayWhole,-3);
% 4. clear defecit sources of all supplied power by setting them back
to
%    the powerSupplyPerSource values.
for(i=1:length(defSources))
    powerState(defSources(i))=powerSupplyPerSource(defSources(i));
end

% 5. distribute power to sources (biggest demand first)
%    if there is no power source big enough - assign to blacked out
defData=sortedDefArray;
for(i=1:length(defData))
    % current zone = (defData(i,1),defData(i,2))
    % current demand = defData(i,3)
    % former supply = defData(i,4)
    % current distance = defData(i,5)
    poweredUp(defData(i,1),defData(i,2),:)=0; % clear old
    for(j=1:sourceCount)
        % if first closest power is available, supply it
        % if not, try second and so on

if(powerState(closestPower(defData(i,1),defData(i,2),j))>=defData(i,3)
&& max(poweredUp(defData(i,1),defData(i,2),:))==0)

powerState(closestPower(defData(i,1),defData(i,2),j))=powerState(closes
tPower(defData(i,1),defData(i,2),j))-defData(i,3);

poweredUp(defData(i,1),defData(i,2),closestPower(defData(i,1),defData(i
,2),j))=1;
        end
    end
    % if none of them are available
    if(max(poweredUp(defData(i,1),defData(i,2),:))==0)
```

```
        % set to blacked out

powerState(sourceCount+1)=powerState(sourceCount+1)-defData(i,3);
        poweredUp(defData(i,1),defData(i,2),sourceCount+1)=1;
    end
end
%------------%
% END SECOND %
%%%%%%%%%%%%%%


%% SECOND- Totals Between -THIRD
powerDemandPerSource=zeros(1,sourceCount); % 1xn - initalize demand to-
tals
for(k=1:sourceCount)
    powerDemandPerSource(k)=sum(sum(poweredUp(:,:,k).*demandMap(:,:)));
end
% powerState is remaining supply (or deficit) for each source
powerState; % from before =(powerSupplyPerSource-powerDemandPerSource);


%% THIRD %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Find all zones powered by biomass regions and keep note of which    %
% region each is powered by. Sort the zones by distance starting with %
% those furthest away. Repower them by clean regions until all clean  %
% power sources are gone.                                             %
%---------------------------------------------------------------------%
%%
[biomassRegions]=[find(supplyRegions(:,5)==(0));find(supplyRegions(:,5)
==(4))];
biomassPowerTotal=0;
for(i=1:length(biomassRegions))

biomassPowerTotal=biomassPowerTotal+powerDemandPerSource(biomassRegions
(i));
end
% If no zones are powered by unclean supplies, skip this loop
%     or if any zones are blacked out, skip the loop too
if(biomassPowerTotal>0 && powerState(sourceCount+1)==0)
    % 1. Identify biomass sources.

[bioSources]=[find(supplyRegions(:,5)==(0));find(supplyRegions(:,5)==(4
))];
    [cleanSources]=find(supplyRegions(find(supplyRegions(:,5)>0),5)<4);
    % 2. get (x,y,power,source,distance) for each zone on a biomass
source
    m=0;
    for(i=1:length(bioSources))
```

```
        % find coordinates and power demand
        % then put them in an array with the source index

[bioX,bioY,bioPower]=find(poweredUp(:,:,bioSources(i)).*demandMap(:,:))
;

bioArray=[bioX,bioY,bioPower,bioSources(i)*ones(length(bioPower),1)];
        % lookup the distance from each zone to the source
        for(j=1:length(bioPower))

bioSourceIndex=find(closestPower(bioX(j),bioY(j),:)==bioSources(i));
            distBio(j)=distancePower(bioX(j),bioY(j),bioSourceIndex);
        end
        % put the data into one package
        bioArrayPlus=horzcat(bioArray,distBio');
        if(m==0)
            bioArrayWhole=bioArrayPlus;
        else
            bioArrayWhole=[bioArrayWhole;bioArrayPlus];
        end
        m=m+1;
        clear bioArray distBio;
    end
    % 3. sort the results by distance (furthest to nearest)
    sortedBioArray=sortrows(bioArrayWhole,-5);
    % 4. distribute power to sources (biggest demand first)
    %    if there is no power source big enough, pass
    % tack on a column to serve as "done" flag
    bioData=horzcat(sortedBioArray,zeros(length(sortedBioArray),1));
    for(i=1:length(bioData))
        % current zone = (bioData(i,1),bioData(i,2))
        % current demand = bioData(i,3)
        % current supply = bioData(i,4)
        % current distance = bioData(i,5)
        % sort by distance to nearest clean source so that
        % we can loop through only clean sources in order of
        % nearest to furthest
        cleanIndex=zeros(length(cleanSources),2);
        for(k=1:length(cleanSources))
            % cleanIndex(k,1) = index
            % cleanIndex(k,2) = source

cleanIndex(k,1)=find(closestPower(bioData(i,1),bioData(i,2),:)==cleanSo
urces(k));

cleanIndex(k,2)=closestPower(bioData(i,1),bioData(i,2),cleanIndex(k,1))
;
        end
```

```
        % sort in order of nearest to furthest
        cleanIndex=sortrows(cleanIndex,1);
        for(j=1:length(cleanSources))
            % if first closest green power is available, supply it
            % if not, try second and so on
            if(powerState(cleanIndex(j,2))>=bioData(i,3) && bioDa-
ta(i,6)==0)
                % subtract power from chosen power source

powerState(cleanIndex(j,2))=powerState(cleanIndex(j,2))-bioData(i,3);
                % add power to old power source

powerState(bioData(i,4))=powerState(bioData(i,4))+bioData(i,3);
                % set poweredUp for chosen to 1 and unchosen to 0
                poweredUp(bioData(i,1),bioData(i,2),cleanIndex(j,2))=1;
                poweredUp(bioData(i,1),bioData(i,2),bioData(i,4))=0;
                bioData(i,6)=1; % flag source as done
            end
        end
        % if no green power sources were available
        if(bioData(i,6)==0)
            % do nothing
        end
    end
end
%----------%
% END LOOP %
%%%%%%%%%%%%

%% FOURTH %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Only runs when Fossil Fuel Power is running. Find all zones powered %
% by the fossil fuel region. Sort the zones by distance starting with %
% those furthest away. Repower them with biomass or transmission until%
% all biomass & transmission sources are gone.                        %
%---------------------------------------------------------------------%
if(supplyRegions(sourceCount,5)==5)
    % locate fossil fuel power sources
    [fossilRegions]=[find(supplyRegions(:,5)==(5))];
    fossilPowerTotal=0;
    for(i=1:length(fossilRegions))

fossilPowerTotal=fossilPowerTotal+powerDemandPerSource(fossilRegions(i)
);
    end
    % run loop only if zones are powered by fossil fuel and none are
    % blacked out
    if(fossilPowerTotal>0 && powerState(sourceCount+1)==0)
        % 1. Identify fossil sources.
```

```
        fossilSources=fossilRegions;
        [nonFossilSources]=find(supplyRegions(:,5)~=5);
        % 2. get (x,y,power,source,distance) for each zone on a fossil
source
        m=0;
        for(i=1:length(fossilSources))
            % find coordinates and power demand
            % then put them in an array with the source index

[fossilX,fossilY,fossilPower]=find(poweredUp(:,:,fossilSources(i)).*dem
andMap(:,:));

fossilArray=[fossilX,fossilY,fossilPower,fossilSources(i)*ones(length(f
ossilPower),1)];
            % lookup the distance from each zone to the source
            for(j=1:length(fossilPower))

fossilSourceIndex=find(closestPower(fossilX(j),fossilY(j),:)==fossilSou
rces(i));

distFossil(j)=distancePower(fossilX(j),fossilY(j),fossilSourceIndex);
            end
            % put the data into one package
            fossilArrayPlus=horzcat(fossilArray,distFossil');
            if(m==0)
                fossilArrayWhole=fossilArrayPlus;
            else
                fossilArrayWhole=[fossilArrayWhole;fossilArrayPlus];
            end
            m=m+1;
            clear fossilArray distFossil;
        end
        % 3. sort the results by distance (furthest to nearest)
        sortedFossilArray=sortrows(fossilArrayWhole,-5);
        % 4. distribute power to sources (biggest demand first)
        %    if there is no power source big enough, pass
        %    tack on a column to serve as "done" flag

fossilData=horzcat(sortedFossilArray,zeros(length(sortedFossilArray),1)
);
        for(i=1:length(fossilData))
            % current zone = (fossilData(i,1),fossilData(i,2))
            % current demand = fossilData(i,3)
            % current supply = fossilData(i,4)
            % current distance = fossilData(i,5)
            % sort by distance to nearest nonfossil source so that
            % we can loop through only clean sources in order of
            % nearest to furthest
```

```
            nonFossilIndex=zeros(length(nonFossilSources),2);
            for(k=1:length(nonFossilSources))
                % cleanIndex(k,1) = index
                % cleanIndex(k,2) = source

nonFossilIndex(k,1)=find(closestPower(fossilData(i,1),fossilData(i,2),:
)==nonFossilSources(k));

nonFossilIndex(k,2)=closestPower(fossilData(i,1),fossilData(i,2),nonFos
silIndex(k,1));
            end
            % sort in order of nearest to furthest
            nonFossilIndex=sortrows(nonFossilIndex,1);
            for(j=1:length(nonFossilSources))
                % if first closest green power is available, supply it
                % if not, try second and so on
                if(powerState(nonFossilIndex(j,2))>=fossilData(i,3) &&
fossilData(i,6)==0) % subtract power from chosen power source

powerState(nonFossilIndex(j,2))=powerState(nonFossilIndex(j,2))-fossilD
ata(i,3); % add power to old power source

powerState(fossilData(i,4))=powerState(fossilData(i,4))+fossilData(i,3)
; % set poweredUp for chosen to 1 and unchosen to 0

poweredUp(fossilData(i,1),fossilData(i,2),nonFossilIndex(j,2))=1;
poweredUp(fossilData(i,1),fossilData(i,2),fossilData(i,4))=0;
                    fossilData(i,6)=1; % flag source as done
                end
            end
            % if no green power sources were available
            if(bioData(i,6)==0)
                % do nothing
            end
        end
    end
end
% END LOOP %
%%%%%%%%%%%%

%% FOURTH - Totals After
powerDemandPerSource=zeros(1,sourceCount); % 1xn - initalize demand to-
tals
for(k=1:sourceCount)
    powerDemandPerSource(k)=sum(sum(poweredUp(:,:,k).*demandMap(:,:)));
end
powerStatistics=horzcat(powerSupplyPerSource',powerDemandPerSource');
newPoweredUp=poweredUp;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepWrapper.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% Controller function.
%
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function
[powerSupplyStats,powerDemandStats,hourlyDemand]=gepWrapper(numHours)
%% RUN FOR 24 HOURS IF NO INPUT
if(nargin==0)
    numHours=24;
end
debug=2; % 1 to make movie, 2 to create figures
% set fileLocation to be used for saved movies and figures
fileLocation=sprintf('../../Thesis/_current/Figures/Analysis/S1/24_hr_d
emo/');

%% LOAD INITIAL VARIABLES
[humWidth,humHeight]=gepVariables();
gepTime=[1,1,1]; % January 1, 1:00AM

% find number of sources -- sourceCount
[supplyData,supplyRegions]=gepSupplyData(gepTime); % no inputs since
gepTime=[1,1,1]
sourceCount=size(supplyRegions,1);

%% Initialize PoweredUp Map
% this loop moved to steadyState
% poweredUp=zeros(length(X),length(Y),sourceCount+1);
% poweredUp(:,:,sourceCount+1)=1; % set all zones to unpowered
% pU(:,:,:,1)=poweredUp; % store initialized poweredUp map

%% Steady State Loop
% 10/14/08 PREPARE A LOOP FOR THE DURATION
%           (1) call gepSupplyData with gepTime to get new data
%           (2) call gepDemandData with gepTime to get new data
%           (3) call gepSupplies with new supplyData
%           (4) call gepDemand with gepTime to get new demand data
%           (5) call gepZones with new demandMap & supplyMap
%           (6) call SteadyState to reorganize the layout
%           (7) increment time by 1 hour
cI=1; % cI=customIndex
```

```
for(m=1:numHours)
    %% GET NEW DATA %%
    [supplyMap]=gepSupplies(gepTime); % get the new supplyMap
    [demandMap]=gepDemand(gepTime); % get the new demandMap
    [supplyData,supplyRegions]=gepSupplyData(gepTime); %TEMPORARY
    %% REDISTRIBUTE POWER %%
    % exceed wind supply. Run gepDistSteadyState to find and fix these
problems

[newPoweredUp,powerStatistics]=gepDistSteadyState(demandMap,supplyMap);
    poweredUp=newPoweredUp;

    %% SAVE POWERED-UP STATE %%
    pU(:,:,:,cI)=newPoweredUp;
    % suppliedPower - total supplied this hour split up by supply
    % generatedPower - total generated this hour
    % demandedPower - total demanded this hour (may match supplied)
    % remainingPower - sum(suppliedPower)-sum(demandedPower)
    powerSupplyStats(cI,:)=powerStatistics(:,1)'; % store hourly power
available
    powerDemandStats(cI,:)=powerStatistics(:,2)'; % store hourly demand
    hourlyDemand(cI)=sum(sum(demandMap));

    %% INCREASE TIME 1 HOUR %%
    monthLengths=[31,28,31,30,31,30,31,31,30,31,30,31];
    if(gepTime(3)==24)
        if(gepTime(2)==monthLengths(gepTime(1)))
            gepTime(1)=gepTime(1)+1;
            gepTime(2)=1;
            gepTime(3)=1;
        else
            gepTime(2)=gepTime(2)+1;
            gepTime(3)=1;
        end
    else
        gepTime(3)=gepTime(3)+1;
    end
    cI=cI+1
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% gepPlot.m
%
% Darrell Ross
% May 2009
%
% GOAL:
% various plots to generate figure
%
% INPUTS:
% plotType -
% 1 - Color Surface Plot of powered cells where the input is
%     HEIGHT x WIDTH x N where N = number of sources + 1
%     each layer N is plotted based on it's source color
% 2 - Source Location Plots - receives a single MxN array of 0s and 1s
%     and plots it with correct colors
% 3 - prints population density map
% 4 - plots hourly power data - receives an MxN array M hours and N
sources
%     plots a stacked bar plot
% 5 - prints up a map template
% plotData - data to be plotted
%
% OUTPUTS: figHandle - handle to the plot
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Function Call
function figHandle=gepPlot(plotType,plotData)
global scenario;
% load unmappedLayer
% 0 = mapped
% 1 = unmapped
load -mat unmappedlayer.mat;

% Choose the plotType and Plot
switch plotType
    case {1}
        %% CASE 1 = color surface plot of powered cell where the input
is
        % HEIGHT x WIDTH x N where N = number of sources + 1
        % each layer N is plotted based on it's source color
        [supplyData,supplyRegions]=gepSupplyData();
        if(scenario==1)
            sourceCount=size(plotData,3); % number of sources
            newColorMap=gepColormap(1);
            colormap(newColorMap);
            for(i=1:sourceCount-1)
```

```
            if(supplyRegions(i,5)==0) % biomass
                plotData(:,:,i)=plotData(:,:,i)*1;
            elseif(supplyRegions(i,5)==4) % transmission
                plotData(:,:,i)=plotData(:,:,i)*2;
            elseif(supplyRegions(i,5)==5) % fossil
                plotData(:,:,i)=plotData(:,:,i)*3;
            else
            end
        end
        plotData=sum(plotData,[3]); % sum the data into one MxN ar-
ray
        plotData=plotData-unmappedLayer';
        %% RUN PLOT
        figHandle=surf(plotData(:,:)');
        caxis([-1 3]);
        view(0,90);
        axis equal;
    elseif(scenario>1) % scenarios 2 and 3
        % get total number of sources (+1)
        sourceCount=size(plotData,3);
        if(scenario==2)
            newColorMap=gepColormap(2);
        elseif(scenario==3)
            newColorMap=gepColormap(3);
        end
        colormap(newColorMap);
        % plotData is X by Y by n
        % where n = number of regions. for each 1 at point (X,Y)
means
        % that zone's power came from source n.
        % Multiplier sets the data to match the colormap settings
        for i=1:sourceCount-1
            plotData(:,:,i)=plotData(:,:,i)*(supplyRegions(i,5)+1);
        end
        % zero out the unsupplied zones list so that when all lay-
ers are
        % summed, unsupplied zones still have a total of 0 (black
on the colormap).
        plotData(:,:,sourceCount)=0;
        plotData=sum(plotData,[3]); % sum the data into one MxN ar-
ray
        plotData=plotData-unmappedLayer';
        %% RUN PLOT
        figHandle=surf(plotData(:,:)');
        caxis([-1 5]);
        view(0,90);
        axis equal;
    end
```

```
    case {2}
        %% CASE 2 - Source Location Plots
        % receives a single MxN array of 0s and 1s
        % and plots it with correct colors
        newColorMap=gepColormap(5); % white;blue
        % shape plotData so that the unmappedLayer can be subtracted
        unmappedMask=2-(unmappedLayer+1)';
        plotData=double(plotData>0); % change to 1's and 0's
        plotData=(plotData+1).*unmappedMask;
        colormap(newColorMap);
        surf(plotData(:,:)');
        view(0,90);
        axis equal;
    case {3}
        %% CASE 3 - prints population density map
        load -mat popdensity.mat % variable popDensity
        popDensity=popDensity*126518; % fill in population per cell
        % shape popDensity so that the unmappedLayer can be subtracted
        unmappedMask=2-(unmappedLayer+1)';
        popDensity=(popDensity).*unmappedMask; %
        colormap('default');
        popDensity=log(popDensity);
        surf(popDensity(:,:)');
        view(0,90);
        axis equal;
        %caxis([-109 7000]);
    case {4}
        %% CASE 4 - plots hourly power data -
        % receives an MxN array M hours and N sources
        % plots a stacked bar plot
        % colors need customized by setting order
        wind=[0.7,0.0,0.9];
        solar=[1,1,0];
        wave=[0,0,1];
        biomass=[0,1,0];
        transmission=[1,0,0];
        fossil=[0.6,0.2,0.0];
        bar(plotData,'stack');
        if(scenario==1)

newColorMap=[biomass;biomass;transmission;transmission;transmission;tra
nsmission;fossil];
        elseif(scenario==2)

newColorMap=[wind;solar;solar;wave;biomass;biomass;biomass];
        elseif(scenario==3)
```

```
newColorMap=[wind;solar;solar;wave;biomass;biomass;biomass;transmission
;transmission;transmission;transmission];
        end
        colormap(newColorMap);
        % prepare figure for paper
        xlabel('Time of Day (hours)','fontsize',12,'fontweight','b');
        ylabel('Power Supply Level (MW)','font-
size',12,'fontweight','b');
        ylim([0 200000]); % set all axes to 200MW max
        set(gca,'yTick',[0 20 40 60 80 100 120 140 160 180 200]*1000);
        set(gca,'yTickLabel',[0 20 40 60 80 100 120 140 160 180 200]);
        set(gcf,'color', 'w'); % set background white
        set(gca,'GridLineStyle',':'); % use '--' for dashed
        set(gca,'YGrid','on');
        set(gca,'FontSize',14);
        hold on;
%         plot(hourlyDemand,'linewidth',2,'color','black');
    case {5}
        %% CASE 5 - prints up a map template
        load -mat unmappedLayer.mat;
        colormap([1,1,1;0,0,0]);
        surf(unmappedLayer);
        view(0,90);
        axis image;
end
```

```
%%%%%%%%%%%%%%%
% gepColormap.m
%
% Darrell Ross
% February 2009
% Version 3.0b
%
% GOAL:
% A colormap setter simply returns a new colormap.
% All colormaps are custom designed for various plots, movies, etc.
%
% INPUTS:
%       mapNum - <1x1 double>
%           1 = 0(black), 1(green), 2(purple), 3(yellow), 4(blue)
%           2 = 1(green), 2(purple), 3(yellow), 4(blue)
%           3 = white, blue
%           4 = white to blue gradient
%%%%%%%%%%%%%%%

function newColorMap = gepColormap(mapNum)
%% set colors
% each color has two handles to facilitate easy handling
fossil=[.99,0.59,.19]; % brown (6)
brown=fossil;
unmapped=[1,1,1]; % white (-)
white=unmapped;
unpowered=[0,0,0]; % black (0)
black=unpowered;
biomass=[0,1,0]; % green (1)
green=biomass;
wind=[0.7,0.0,0.9]; % purple (2)
purple=wind;
solar=[1,1,0]; % yellow (3)
yellow=solar;
wave=[.6,.6,1]; % blue (4)
blue=wave;
transmission=[1,0,0]; % red (5)
red=transmission;
%%
switch mapNum
    case {1}
        %% Scenario 1
        newColorMap=[unmapped;
            unpowered;
            biomass;
            transmission;
            fossil];
    case {2}
```

```
        %% Scenario 2
        newColorMap=[unmapped;
            unpowered;
            biomass;
            wind;
            solar;
            wave];
    case {3}
        %% Scenario 3
        newColorMap=[unmapped;
            unpowered;
            biomass;
            wind;
            solar;
            wave;
            transmission];
    case {4} % maps a gradient of white(min) to blue(max)
        %% case 4
        c1=[0,1:-0.1:0];
        c2=[0,1:-0.1:0];
        c3=[0,ones(1,11)];
        newColorMap=horzcat(c1',c2',c3');
    case {5} % maps black(unmapped), white(empty_cells), blue(sup-
ply_location)
        %% case 3
        newColorMap=[[0,0,0];white;blue];
end
```