EFFECTS OF GLOBAL WARMING ON TRANSMISSION LINE SAG

A Thesis by

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The following faculty have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

Ward Jewell, Committee Chair

Visvakumar Aravinthan, Committee Member

Ikramuddin Ahmed, Committee Member

DEDICATION

To my parents, for their unwavering support
and guidance

ABSTRACT

Global warming has forced the power industry to adapt its infrastructure and develop technology in order to mitigate the effects and reduce the extent to which it will affect the operation of the electrical grid. With this goal in mind, the project attempts to quantify the effect of global warming on transmission line sag. First, a climate model that could predict temperature data for the time period (2001-2100) was needed. Next, a relationship between temperature and electricity demand needed to be quantified. Using this relationship and the temperature values generated by the climate model, the predicted electricity demand values were calculated for the examined time period. Since the voltage at which power is transported remains constant, the rate at which power is delivered will be given by the current flowing through the conductor. Using the estimated current values, the temperature of the conductor was calculated. This value is then used to calculate incremental sag due to the additional electrical demand.

The calculated incremental sag is then plotted across time to show the increase in sag as temperatures increase. The plots also show various spikes in transmission line sag values ranging from less than an inch to just over two inches over the examined time period which does not significantly affect the operation of the grid. However, the project was performed using ideal values and is only a best case scenario. Overall, the project was successful in establishing that a relationship between global warming and transmission sag does exist, and that it needs to be addressed during future infrastructure planning.

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LIST OF ABBREVIATIONS / NOMENCLATURE

GCM	General Circulation Model or Global Climate Model
GHG	Greenhouse Gas
NCDC	National Climatic Data Center
EPA	Environmental Protection Agency
IPCC	International Panel on Climate Change
DOE	Department of Energy
EIA	Energy Information Administration
CU	Copper Conductor
ACSR	Aluminum Conductor Steel Reinforced
AAAC	All Aluminum Alloy Conductor
KCC	Kansas Corporation Commission
IEEE	Institute of Electrical and Electronic Engineers
NESC	National Electrical Safety Code

CHAPTER 1

INTRODUCTION

Climate change, specifically, global warming is an issue that is now at the forefront of countless political and scientific agendas. The industrial revolution and the fossil fuels that have fueled it have taken a toll on the environmental well-being of the Earth. We are now observing and experiencing these effects through increasingly unpredictable weather, hurricanes and tornados with increasing frequency and intensity [1]. Increase in greenhouse gas emissions and concentration levels have caused an uptick in respiratory illnesses, especially in big cities [2]. As a result of these events, considerable time and money are now being devoted to find a way to mitigate global warming and improve the environment.

One industry that contributes significantly to increasing levels of greenhouse gases in the atmosphere is the electricity industry. However, in the modern world, electrical power is now essential to our survival. Hence there is now increased interest in renewable energy generation technologies that can provide clean and sustainable power without damaging the environment. Although ample research has been conducted to finding a solution to the problem of generating clean power, the effects of global warming on the rest of the power industry have been largely neglected and under-researched. Such effects include severe weather, rising sea levels/ land subsidence, changing precipitation pattern, and changing vegetation [3]. An efficient and effective transmission and distribution system is of great importance if we wish to transport the power generated to the load centers.

Given the size and complexity of the power grid any changes that need to be instituted will require a great deal of meticulous planning and time. As a result, it is important to understand the long term effects of global warming on the power grid. One of the effects to consider is that of transmission line sag. Transmission line conductors sag as a result of current flowing through them. This current causes the temperature of the conductor to increase which then results in the expansion of the conductor. Upon expansion the conductor "sags" causing a bow in the line. Excessive transmission line sag could cause a loss in clearance which could result in an interruption in power flow, flashover current which could then result in safety issues.

This project will attempt to investigate the effects of global warming on transmission line sag. In addition, we will try to quantify the relationship and provide a long term estimate of how global warming affects transmission line sag.

CHAPTER 2

LITERATURE REVIEW

In the effort to determine the relationship between global warming and transmission line sag, the first step was finding either a suitable model to generate data or extracting data from previously simulated runs. The temperature data required was for the state of Kansas. However, further research using the National Climatic Data Center (NCDC) [4] indicated that General Circulation Model (GCM) data was generated and stored according to latitudes and longitudes. As a result the focus shifted towards finding temperature data based on the approximate latitude and longitude location of the city of Wichita.

The Environmental Protection Agency (EPA) displays a global climate projections graph on its climate change webpage [5]. The graph charted climate projections from various GCM's. These projections were included in the IPCC Fourth Assessment Report. These GCM's took into account many parameters and variables to generate climate projections as accurately as possible. But the most important and heavily weighted parameter was Greenhouse Gas (GHG) concentrations. The models used historical data to predict the rate at which GHG concentrations have been increasing and generating future GHG levels. By taking these values and substituting them into a series of formulae, these models were able to provide long term climate projections for many parameters (such as temperature, wind speeds, humidity, etc.).

However, finding the detailed tabulated temperature proved difficult for a number of reasons. First, this data was only available through secure login that had to be requested from the NCDC website. Second, since the size of the file was enormous, all the data downloaded was encoded to save space and to make it portable. Decoding software/programs was required. Eventually decoding programs [6] were found and the temperature data required was successfully extracted from these files.

Using the extracted temperature however, would be meaningless unless a plausible relationship between temperature fluctuations and electrical load variations was modeled. Since it was these load values that were eventually used to calculate transmission line sag, it was of paramount importance that a sound model was created.

The research was geared towards finding a way to successfully quantify the relationship between temperature and electrical loads. A couple of research papers met the requirements, but the papers were based on European climate models and European market demand [7]. These parameters were dissimilar from the American models that the required model needed to be based on since the weather patterns and the way the power industry is constituted in Europe vary vastly from America. Further research led to finding a paper [8] which detailed a model quantifying the relationship between load and temperature. In addition, this model was performed using data for the state of California. Using this template, the needed relationship was quantified and using this relationship, electrical demand was projected for the analyzed time period.

Next, in order to apply the data extracted and calculated so far, information about the currently existing transmission infrastructure in Kansas was needed. The data needed was found in the Kansas Transmission line map [9].

This information was then used to calculate a sag estimate. But, finding a reasonable way to estimate the sag was needed to complete the project. There are existing papers that detail various ways to calculate sag [10, 11, and 12]. The industry standard when estimating sag for transmission line stringing purposes is the SAG10 software [13] marketed by Southwire [14]. But this software required extensive training to operate and also gave unique estimates based on terrain, span length, span height, etc. The software modeled each line one by one and gave a sag estimate when stringing transmission lines. This proved to be unnecessarily complicated and beyond the scope of this project. This led to finding a way to estimate the sag using simple formulae and a small number of inputs which would be adequate with the length of the time frame under analysis and the idealized nature of the model developed so far.

Necessary for these calculations were certain constant and variable values for the transmission line conductors, which were needed to estimate the sag. They included parameters such as ampacity and estimated temperature of the conductors. The ampacity values were provided by Don Taylor, PE at Westar Energy. Then, a conductor temperature calculator [23] was found which calculated the estimated temperature of the specific conductor based on the magnitude of current flowing through it. The calculator is based on the IEEE standard 738 [15] which provides details to the industry standard method to calculate conductor temperature.

CHAPTER 3

RESEARCH STATEMENT

The goal of this project was to investigate the effects of global warming on transmission line sag. As stated earlier, transmission line sag is caused by the current flowing through the conductors. This current raises the temperature of the conductor which causes the metal to expand and hence “sag”.

The first step was to find a general circulation model (GCM) in order to extract long term temperature projections by taking into account global warming. While looking at long term global warming effects, the temperature was the only parameter considered. Other parameters such as humidity, precipitation, wind speeds, frequency of storms and unpredictable weather are taken into account when building the general circulation models. However, it became apparent in the project’s infancy that considering all these parameters would be beyond the scope of this project. In addition, it was determined that the inclusion of the most significant parameter (temperature) would aid in the completion of the first step before future research could incorporate the rest of the neglected parameters.

Next, it was determined that a relationship between temperature variation and electrical load had to be quantified. In an effort to accomplish this, the methodology was based on the model detailed in Franco’s research paper [16]. Using this relationship, it was possible to project long term electrical loads with increasing temperatures. Again, the only parameter considered was temperature. Factors such as population, rising electricity consumption, etc. were neglected in an effort to avoid over-complicating the project.

The projected electrical loads were then used to calculate sag for the intended time frame. For the sag calculations, the formulae detailed by Du & Liao [8] were used. As before, factors other than temperature, such as, ice and wind loading, unpredictable weather, were neglected. In addition, only level spans were considered in the sag calculations. However considering the relatively flat topography of Kansas and the lack of transmission lines in the few non- level areas such as the Flint Hills, it is a reasonable assumption.

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Climate Model

As specified earlier, the first step of this project was to obtain projected temperature values starting from the year 2000 to 2100. In addition, it was also determined that more than one model would provide a of range results which takes into account various scenarios and different rate of GHG emissions. Hence, different results are obtained depending on the change in the rate of GHG emissions being released into the atmosphere.

Research into climate models indicated that the most reliable and widely accepted climate projections were those published in IPCC's "Fourth Assessment Report" [17]. It was decided that these are the models that would be used to extract climate/temperature data.

Figure 4.1 depicts the results of the three models plotted against time and shows the variation in the models. Model A1b generates climate data based on the average rate at which emissions are currently rising. Model A2 generates climate data based on a higher rate of GHG emission. Model B1 generates climate data based on GHG emission being released into the atmosphere at a rate lower than the present time.

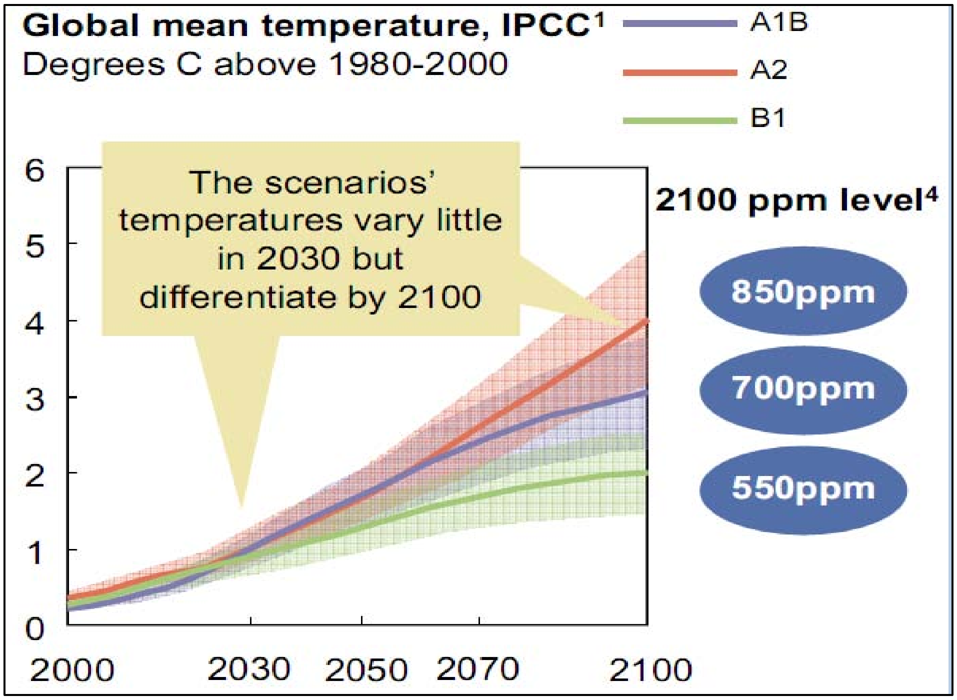

Figure 4.1: IPCC's Fourth Assessment Report: Climate Change, 2007

Further searches revealed that the datasets that were generated by the same climate model used in the IPCC Fourth Assessment Report could be found at the IPCC Data Distribution Center website [18]. The website contained a list of climate models created and simulated by various research centers from around the world. For this project, the Geophysical Fluid Dynamics Laboratory Center (GFDL) was chosen. The latest version, CM2.1, of the model created was chosen. In addition, the PI-cntrl run-1 data set was selected to be downloaded. Among these dataset, the project only required near surface air temperature. As a result only information pertaining to this parameter was downloaded [19].

However, before, these datasets could be downloaded a login was needed to access the download links. This access was provided by the IPCC Data Distribution

Center to Dr. Ward Jewell upon request, who was in turn was able to download the required dataset. Another issue with the dataset was that of encoding. Since the size of the dataset was so large, the IPCC Data Distribution Center datasets were all encoded to save space and make these datasets more accessible and downloadable. The datasets were encoded in either “grib” or “netCDF”. In order to view and extract the required data, decoding software was required. This software was found and downloaded which enabled the data to be decoded and placed in Excel files. This software was found online [6] and downloaded as an extension for Excel.

The data could now be viewed in Excel. The temperature data in the excel file was sorted by months with values ranging from 1-1200 which represented 12 months every year for 100 years. The temperature values were in Kelvin. The data set was also sorted location wise using latitude and longitude values. The latitudinal and longitudinal location for Wichita, KS was used. Also, since the project is only looking at sag during the summer months, temperature data for the months of May, June, July and August were used. The temperature data from these months was then averaged and then converted into Fahrenheit using equations 4.1&4.2

$$\text{Celsius} = \text{Kelvin} - 273.15 \tag{4.1}$$

$$\text{Fahrenheit} = (9/5 * \text{Celsius}) + 32 \tag{4.2}$$

These values were then plotted against time for all three IPCC models (A1b, A2, and B1) as shown in figures 4.2, 4.3 & 4.4.

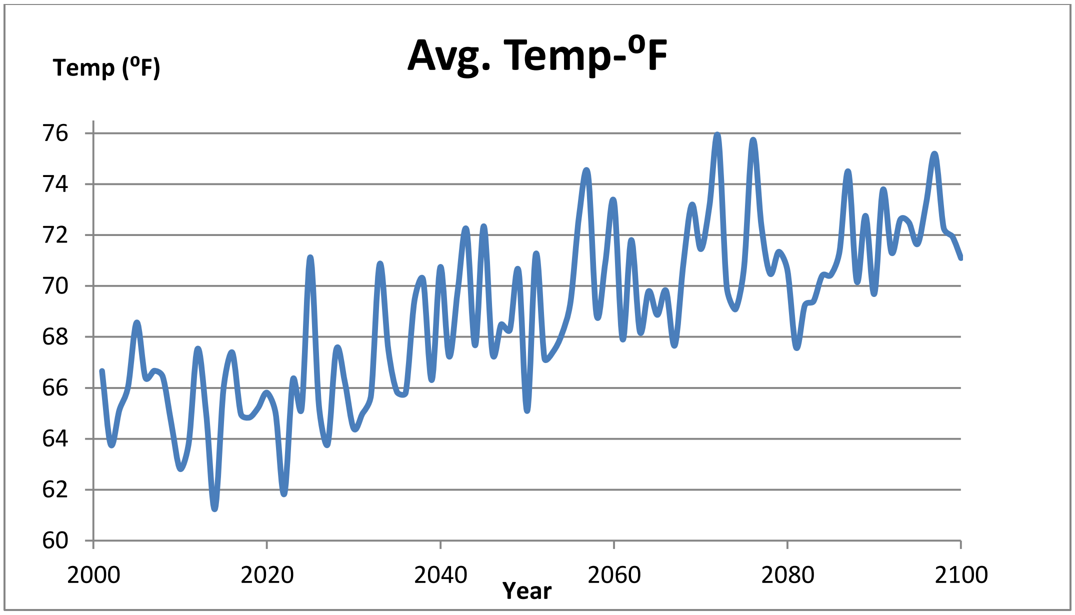

Figure 4.2: Average Forecast May through August Temperatures in Kansas, IPCC Model A1b

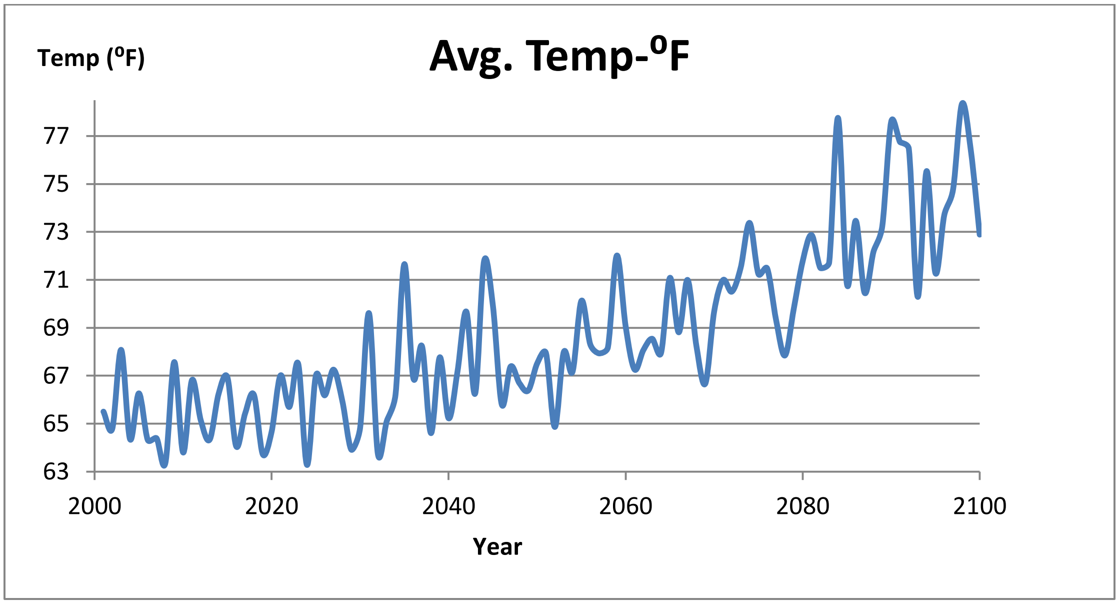

Figure 4.3: Average Forecast May through August Temperatures in Kansas, IPCC Model A2

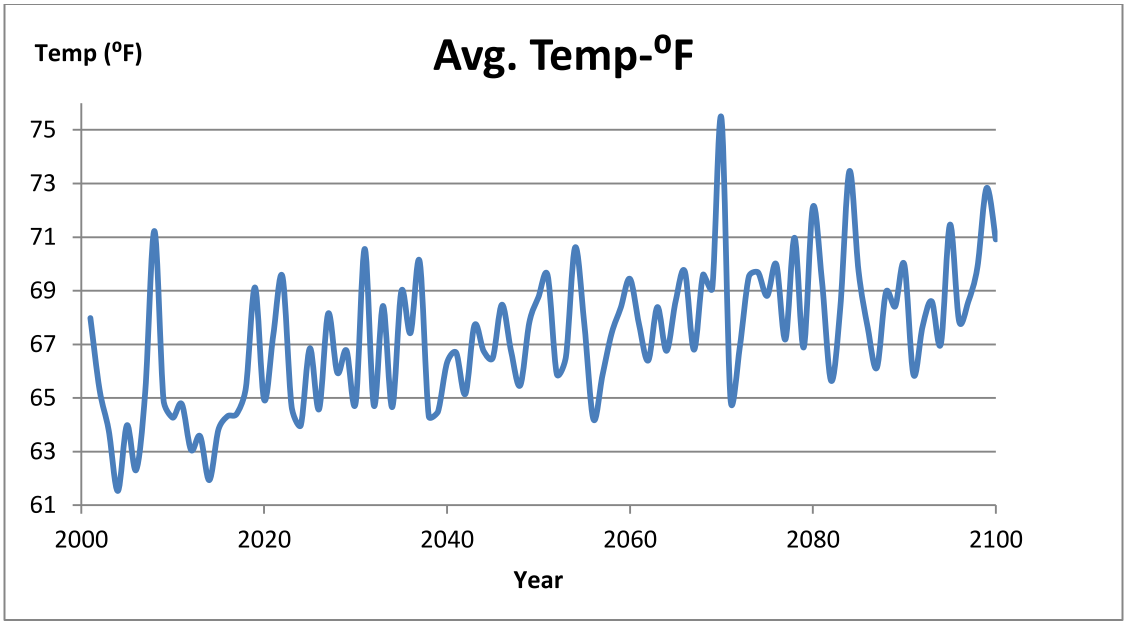

Figure 4.4 Average Forecast May through August Temperatures in Kansas, IPCC Model B1

4.2 Relationship between Electricity Demand and Temperature

The next step, now that the temperature data has been extracted and converted to Fahrenheit, was to estimate and quantify the behavior of electricity demand when under the projected temperature conditions. This relationship would result in estimating the electricity demand for the region of Wichita from 2000-2100.

In order to accomplish this, an equation that relates electricity demand to temperature for Wichita needed to be derived. As a result, historical data was used to derive this equation. The NCDC website provided average temperature data for every month from 1996 to 2011 [20]. Again as before, only the summer months were taken into consideration. Then, electricity consumption data for the same period for the state of Kansas was found on the EIA website [21]. Using these datasets, it was then possible to plot these values against each other and fit a trend line to them using Excel. The equation of this trend line was then found and displayed using Excel. This plot is shown in Figure 4.5.

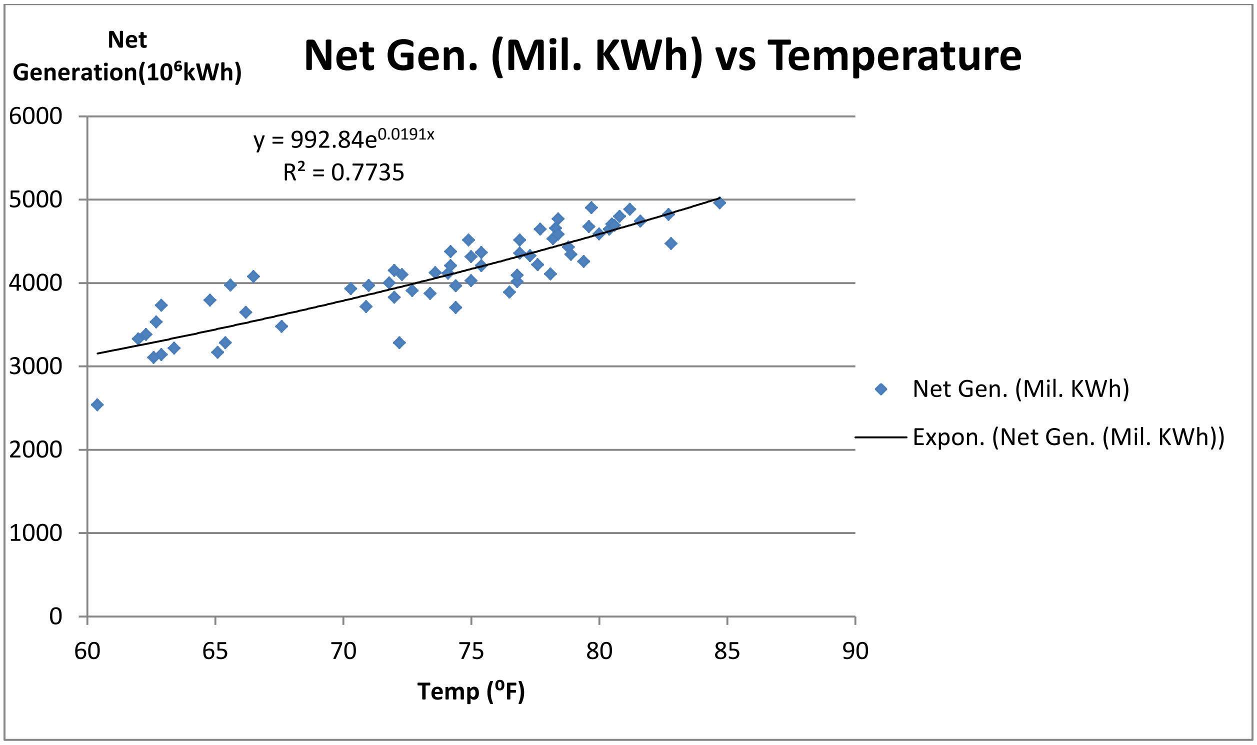

Figure 4.5: Kansas Net Generation

As seen in figure 4.5, an exponential trend line was used. The linear trend line did not adequately quantify the relationship between electricity and temperature and was hence not used.

4.3 Electricity Generation projections

With the relationship between electricity generation and temperature obtained, the next step was to use this equation to find values of the electricity generation from 2000-2100. This was accomplished by once again using Excel to calculate the electricity

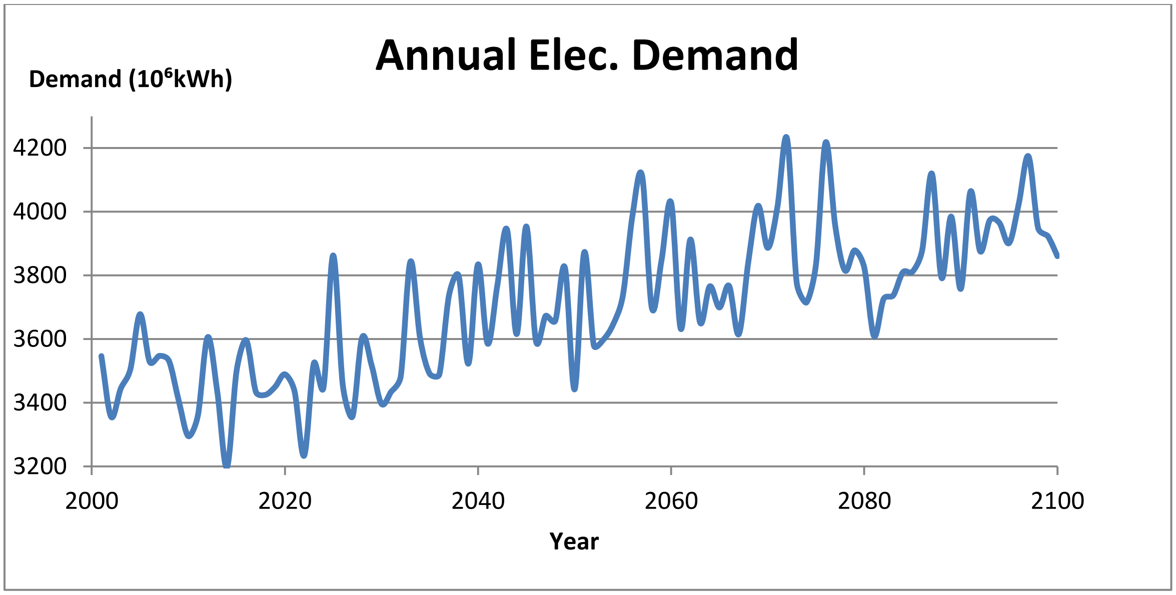

Figure 4.6: Annual Electricity Demand based on Average Forecast Temperatures in Kansas, IPCC Model A1b

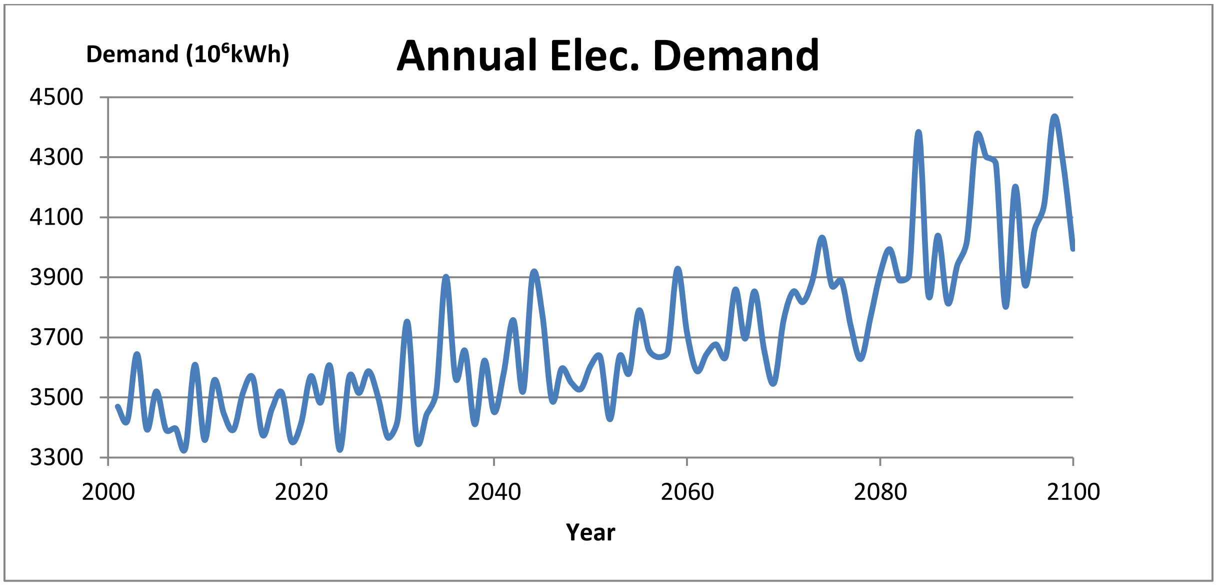

Figure 4.7: Annual Electricity Demand based on Average Forecast Temperatures in Kansas, IPCC Model A2

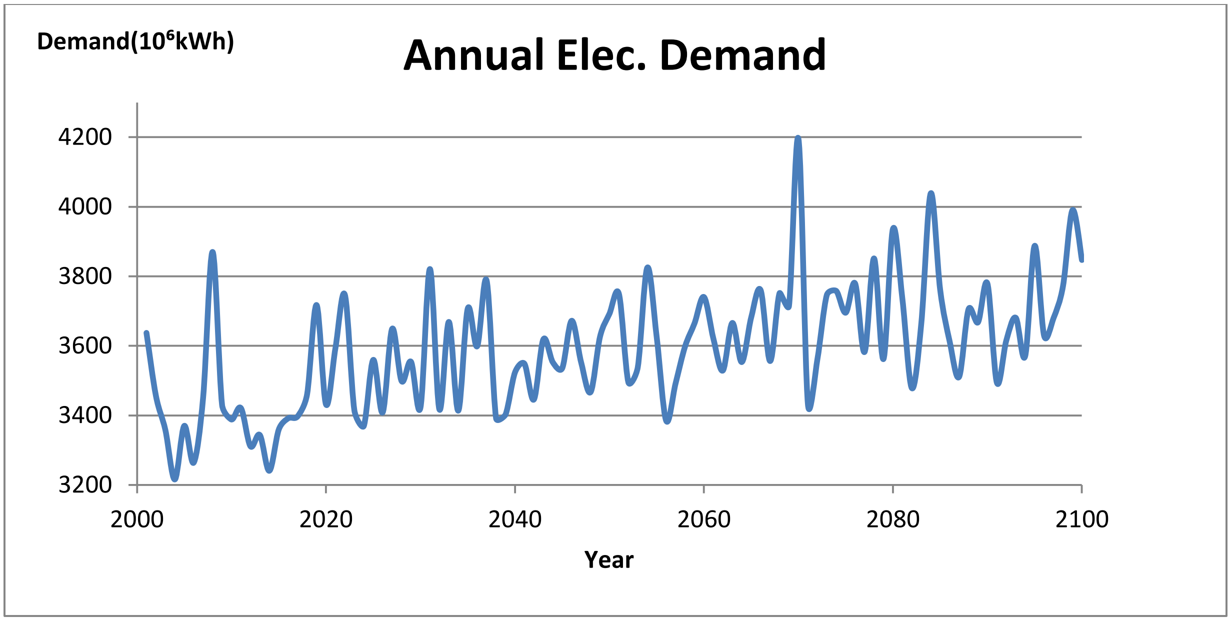

Figure 4.8: Annual Electricity Demand based on Average Forecast Temperatures in Kansas, IPCC Model B1

generation values based on the temperature projections obtained from the climate model datasets. Figures 4.6, 4.7 & 4.8 are plots of electricity generation versus time for the three different models.

4.4 Transmission Line Conductor Specifications

In order to proceed to the transmission line sag calculations, certain parameters and information about the existing transmission line infrastructure in the state of Kansas are needed. This information was found from the Kansas Corporation Commission website [9], which specifies the various voltages at which electricity is transmitted in Kansas, and the length of these lines.

Using this information, it was then possible to find the exact specifications of the conductors that were used for power transmission at these various voltages. Table 4.1 lists the conductors which are used for transmission. They are sorted by the transmission voltage level.

Table 4.1: List of Conductors Used for Various Voltage Levels

Voltage Level (KV)	Conductors
34.5	2/0 CU; 4/0 CU; 4/0 ACSR; 266.8 ACSR; 477 ACSR; 556.5 ACSR
69	4/0 CU; 4/0 ACSR; 266.8 ACSR; 556.5 ACSR; 795 ACSR; 954 ACSR; and 1192.5 ACSR
115	4/0 ACSR; 266.8 ACSR; 556.5 ACSR; 795 ACSR; 1192.5 ACSR; and 2x1192.5 ACSR
138	266.8 ACSR; 477 ACSR; 954 ACSR; 2x666.6 ACSR; 2x795 ACSR; 2x954 ACSR; 1192.5 ACSR; and 2x1192.5 ACSR
161	795 ACSR
230	795 ACSR; 9272. AAAC; and 1192.5 ACSR
345	2x795 ACSR; 2x954 ACSR; and 2x1192.5 ACSR

Where,

CU: copper conductor

ACSR: Aluminum Conductor Steel Reinforced

AAAC: All Aluminum Alloy Conductor

Based on Table 4.1, the conductor specifications were then looked up and found from Southwire product specifications documents.

4.5 Sag Calculations

As stated earlier, there are many ways to calculate sag. The calculation methodology used depends on the purpose for which these sag calculations are needed.

For instance, the industry standard software for sag calculations is SAG10. However, the software is mainly used for transmission line stringing purposes to estimate the amount of tension with which to string the line and the amount of reasonable sag that should be allowed in order for the line to function properly. In this project however, the goal is to obtain a direct relationship between increase in transmission line sag and global warming. With these considerations in mind and research into sag calculations methods, a paper published on the IEEE Xplore website was found.

The paper," Online Estimation of Power Transmission Line Parameters, Temperature and Sag" by Du & Liao [8], details a methodology to calculate transmission line sag based on the temperature of the transmission line conductor. The paper uses a series of equations (4.4, 4.5, 4.6, 4.7 & 4.8) to estimate the transmission line sag.

But, before these formulae can be used, there are certain parameters that need to be found first. The horizontal tension component (H) is proportional to the rated strength of the conductor and needs to be calculated for every conductor for which sag is calculated. Also, the weight for each conductor needs to be specified. The weight and reference resistance for each conductor were found from the product specifications for each conductor from the Southwire website [22]. The horizontal tension component (H) can be found as:

$$H = \frac{(w \times s)}{2} \times \sqrt{\frac{s}{6 \times slack}} \tag{4.3}$$

Where s is the span of the transmission line, slack refers to the difference between the length of a conductor hanging between two towers and the span length between the attachment points on those towers, and w is the weight of the transmission line for the given span [22].

Next, the reference sag, D_{ref}, is given by equation 4.4

$$D_{ref} = \frac{w \times s^2}{8 \times H} \tag{4.4}$$

Using the reference sag calculated in equation 4.4, the conductor length $L_{T_{ref}}$ due to reference sag D_{ref} at reference temperature is calculated as shown in equation 4.5.

$$L_{T_{ref}} = s + \frac{8 \times {D_{ref}}^2}{3 \times s} \tag{4.5}$$

Table 4.2: Conductor Co-Efficients

Conductors	**Code Name**	***$\alpha_{20°C}$, /°C**	****α, %/°F**
2/0 CU	CU 2/0 7	0.00381	0.00094
4/0 CU	CU 4/0 12	0.00381	0.00094
4/0 ACSR	Penguin	0.00404	0.00074
266.8 ACSR	Partridge	0.00404	0.00073
477 ACSR	Hawk	0.00404	0.00073
556.5 ACSR	Dove	0.00404	0.00073
795 ACSR	Drake	0.00404	0.00073
954 ACSR	Cardinal	0.00404	0.00078
1192.5 ACSR	Grackle	0.00404	0.00081
2*666.6 ASCR	Flamingo/VR2	0.00404	0.0008
927.2 AAAC	Greeley	0.00347	0.00128
2x795 ACSR	Drake/VR2	0.00404	0.00073
2x954 ACSR	Cardinal/VR2	0.00404	0.00078
2x1192.5 ACSR	Grackle/VR2	0.00404	0.00081

*Temperature Coefficient of Resistance
**Coefficient of Linear Thermal Expansion

The coefficient of thermal linear expansion and the thermal resistivity coefficient were also found from Southwire and provided by Drew Pearson, EIT Southwire Inc. These values are listed in Table 4.2.

Now that all the reference values were calculated, it was time to establish a link between the changing climate data and transmission line sag. In order to quantify this relationship, simple power equations were used. Since $P=V*I$, and the voltage of the conductors at which the power is being transmitted, neglecting minor voltage drops, remains constant, we can assume that $P \, a \, I$. Hence any change in electric power demand will be mirrored in the current flowing through the conductors. Therefore the percentage (%) change in electrical demand was found for the entire time period using 2001 as the base year. Consequently, using the ampacity values of the conductors, provided by Don Taylor, PE at Westar Energy, under normal conditions, values of current flowing through conductors initially loaded at 50% and 80% of their amapcity were calculated. Ampacity is the maximum amount of current that a conductor can carry under its present conditions. Then, using the percentage change in electrical demand, these current values were then extrapolated for the entire time period.

The next step was to find the estimated temperature of the conductor at the present current loading. But after extensive research, it was found that there is no single equation that relates current to conductor temperature. Instead it was decided that a conductor temperature calculator would be used [23]. The calculator is based on IEEE Standard 738(*IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors*) [15].

Using the estimated temperature T_{est} results from this calculator, along with the coefficients listed in Table 4.2 and the values of $L_{T_{ref}}$, the next equation (4.6) determines the conductor length due to sag $L_{T_{est}}$ at the estimated temperature T_{est} of the transmission line.

$$L_{T_{est}} = L_{T_{ref}}\left[1 + \alpha_{AS}\left(T_{est} - T_{ref}\right)\right] \qquad (4.6)$$

Where, α_{AS} is the coefficient of linear thermal expansion. Finally the estimated sag of the conductor, D_{est}, was found by using equation 4.7.

$$D_{est} = \sqrt{\frac{3 \times s\left(L_{T_{est}} - s\right)}{8}} \qquad (4.7)$$

Using these equations, the estimated sag for each conductor was calculated for the entire time period (2001-2100) in Excel.

CHAPTER 5

RESULTS

Using the methodology discussed in Chapter-4, the sag values for the entire time period examined (2001-2100) were obtained based on all three climate models(A1b, A2, B1). Tables 5.1, 5.2, 5.3 show summary examples of these sag calculations since the size of the data tables precludes it from being displayed in this document. Hence, a few of the values are displayed to give an idea of the values obtained. The tables display transmission line sag values in feet, calculated for all the conductors, at every voltage level for a of couple years at initially 50% and 80% ampacity loading.

The tables are able to demonstrate and show just how much the sag increases as time passes. The sag increases range in values from two feet to eleven feet. These increases in sag will cause the conductors to violate the mandated buffer zones that must exist between the minimum clearance and required clearance. Also, it must not be forgotten that only normal loadings were taken into account. If emergency loadings were also considered, a greater occurrence of this buffer violation would be seen. Not only will this lead to non-compliance with electrical codes resulting in government imposed fines for utilities, but also increases the risk of direct contact with vegetation or creating a short circuit with the ground if the lines sag low enough. Both of these scenarios can result in power flow being interrupted.

Table 5.1: Summary of Transmission Line Sag Calculations for IPCC Model A1b

	Conductor Sag (ft), IPCC Model A1b			
Conductor/Voltage (kV)	2002 @50%	2072 @ 50%	2002 @80%	2072 @80%
34.5 (2/0 CU)	23.813	23.8504	23.913	24.012
34.5 (4/0 CU)	23.82	23.854	23.917	24.02
34.5 (4/0 ACSR)	23.79	23.81	23.85	23.92
34.5 (266.8 ACSR)	23.79	23.821	23.88	23.942
34.5 (477 ACSR)	23.8	23.823	23.87	23.94
34.5 (556.5 ACSR)	23.8	23.823	23.87	23.94
69 (4/0 CU)	38.84	38.88	38.95	39.06
69 (4/0 ACSR)	38.805	38.832	38.88	38.954
69 (266.8 ACSR)	38.814	38.844	38.9	38.98
69 (556.5 ACSR)	38.82	38.85	38.9	38.975
69 (795 ACSR)	38.82	38.849	38.9	38.975
69 (954 ACSR)	38.83	38.858	38.91	38.995
69 (1192.5 ACSR)	38.833	38.865	38.92	39.01
115 (4/0 ACSR)	58.21	58.247	58.32	58.432
115 (266.8 ACSR)	58.22	58.267	58.34	58.467
115 (556.5 ACSR)	58.23	58.27	58.35	58.463
115 (795 ACSR)	58.23	58.273	58.35	58.463
115 (1192.5 ACSR)	58.251	58.298	58.38	58.508
115 (2*1192.5 ACSR)	58.251	58.298	58.38	58.508
138 (266.8 ACSR)	58.22	58.267	58.34	58.467
138 (477 ACSR)	58.226	58.269	58.34	58.463
138 (954 ACSR)	58.242	58.287	58.365	58.493
138 (2*666.6 ACSR)	58.242	58.288	58.368	58.498
138 (2*795 ACSR)	58.234	58.273	58.346	58.463
138 (2*954 ACSR)	58.242	58.287	58.365	58.493
138 (1192.5 ACSR)	58.251	58.297	58.38	58.508
138 (2*1192.5 ACSR)	58.251	58.297	58.38	58.508
161 (795 ACSR)	61.55	61.6	61.686	61.823
230 (795 ACSR)	62.92	62.973	63.07	63.212
230 (927.2 AAAC)	63.055	63.151	63.316	63.58
230 (1192.5 ACSR)	62.95	63.004	63.106	63.2685
345 (2*795 ACSR)	77.641	77.697	77.795	77.95
345 (2*954 ACSR)	77.66	77.716	77.82	77.991
345 (2*1192.5 ACSR)	7.67	77.73	77.84	78.011

Table 5.2: Summary of Transmission Line Sag Calculations for IPCC Model A2

Conductor/Voltage (kV)	Conductor Sag (ft), IPCC Model A2			
	2004 @50%	2074 @ 50%	2004 @80%	2074 @80%
34.5 (2/0 CU)	23.817	23.845	23.924	24
34.5 (4/0 CU)	23.822	23.85	23.928	24.004
34.5 (4/0 ACSR)	23.789	23.807	23.859	23.911
34.5 (266.8 ACSR)	23.798	23.818	23.876	23.932
34.5 (477 ACSR)	23.794	23.819	23.876	23.93
34.5 (556.5 ACSR)	23.801	23.8204	23.876	23.93
69 (4/0 CU)	38.845	38.875	38.962	39.045
69 (4/0 ACSR)	38.809	38.828	38.886	38.943
69 (266.8 ACSR)	38.818	38.84	38.905	38.966
69 (556.5 ACSR)	38.822	38.843	38.905	38.964
69 (795 ACSR)	38.824	38.845	38.906	38.965
69 (954 ACSR)	38.83	38.854	38.92	38.983
69 (1192.5 ACSR)	38.837	38.86	38.928	38.99
115 (4/0 ACSR)	58.214	58.241	58.33	58.414
115 (266.8 ACSR)	58.228	58.26	58.357	58.45
115 (556.5 ACSR)	58.232	58.265	58.357	58.446
115 (795 ACSR)	58.2354	58.2682	58.3586	58.447
115 (1192.5 ACSR)	58.256	58.291	58.3926	58.491
115 (2*1192.5 ACSR)	58.256	58.291	58.3926	58.491
138 (266.8 ACSR)	58.228	58.26	58.357	58.449
138 (477 ACSR)	58.221	58.2635	58.357	58.446
138 (954 ACSR)	58.247	58.282	58.38	58.475
138 (2*666.6 ACSR)	58.2472	58.2831	58.384	58.481
138 (2*795 ACSR)	58.2354	58.2682	58.3586	58.447
138 (2*954 ACSR)	58.2467	58.282	58.38	58.475
138 (1192.5 ACSR)	58.256	58.291	58.3926	58.491
138 (2*1192.5 ACSR)	58.256	58.291	58.3926	58.491
161 (795 ACSR)	61.56	61.594	61.701	61.805
230 (795 ACSR)	62.926	62.97	63.081	63.19
230 (927.2 AAAC)	63.0657	63.14	63.35	63.544
230 (1192.5 ACSR)	62.952	62.995	63.1234	63.25
345 (2*795 ACSR)	77.65	77.7	77.81	77.93
345 (2*954 ACSR)	77.66	77.71	77.84	77.97
345 (2*1192.5 ACSR)	77.675	77.721	77.86	77.99

Table 5.3: Summary of Transmission Line Sag Calculations for IPCC Model B1

Conductor/Voltage (kV)	Conductor Sag (ft), IPCC Model B1			
	2006 @50%	2070 @ 50%	2006 @80%	2070 @80%
34.5 (2/0 CU)	23.807	23.843	23.895	23.994
34.5 (4/0 CU)	23.811	23.848	23.9	24
34.5 (4/0 ACSR)	23.783	23.806	23.84	23.91
34.5 (266.8 ACSR)	23.789	23.817	23.855	23.93
34.5 (477 ACSR)	23.7921	23.819	23.855	23.93
34.5 (556.5 ACSR)	23.793	23.819	23.857	23.93
69 (4/0 CU)	38.833	38.874	38.931	39.04
69 (4/0 ACSR)	38.802	38.827	38.865	39.94
69 (266.8 ACSR)	38.809	38.84	38.882	38.963
69 (556.5 ACSR)	38.813	38.842	38.883	38.961
69 (795 ACSR)	38.82	38.843	38.884	38.962
69 (954 ACSR)	38.824	38.853	38.967	38.98
69 (1192.5 ACSR)	38.828	38.86	38.904	38.991
115 (4/0 ACSR)	58.203	58.241	58.297	58.41
115 (266.8 ACSR)	58.214	58.259	58.323	58.44
115 (556.5 ACSR)	58.22	58.263	58.324	58.441
115 (795 ACSR)	58.223	58.265	58.326	58.443
115 (1192.5 ACSR)	58.242	58.29	58.3564	58.486
115 (2*1192.5 ACSR)	58.242	58.29	58.3564	58.486
138 (266.8 ACSR)	58.214	58.259	58.323	58.44
138 (477 ACSR)	58.218	58.262	58.323	58.44
138 (954 ACSR)	58.237	58.28	58.345	58.47
138 (2*666.6 ACSR)	58.234	58.281	58.35	58.476
138 (2*795 ACSR)	58.223	58.265	58.326	58.443
138 (2*954 ACSR)	58.237	58.280	58.345	58.47
138 (1192.5 ACSR)	58.2422	58.29	58.356	58.486
138 (2*1192.5 ACSR)	58.2422	58.29	58.356	58.486
161 (795 ACSR)	61.541	61.591	61.66	61.8
230 (795 ACSR)	62.91	62.963	63.04	63.19
230 (927.2 AAAC)	63.038	63.134	63.271	63.534
230 (1192.5 ACSR)	62.935	62.99	63.078	63.24
345 (2*795 ACSR)	77.631	77.689	77.768	77.924
345 (2*954 ACSR)	77.65	77.71	77.79	77.96
345 (2*1192.5 ACSR)	77.66	77.72	77.81	77.98

Figures 5.1-5.21 plot the sag versus year for every voltage level for all three models to show which way sag trends. Note that although the plots show that the slopes of most of these plots are small, it is the increase in magnitude of the peak value that must be examined. This is because outages occur the instant there is a short circuit. Whether it is a gradual increase or sudden spike in electrical loads that causes the sag of the conductors, either scenario could interrupt power flow and eventually cause a blackout if it is left unchecked.

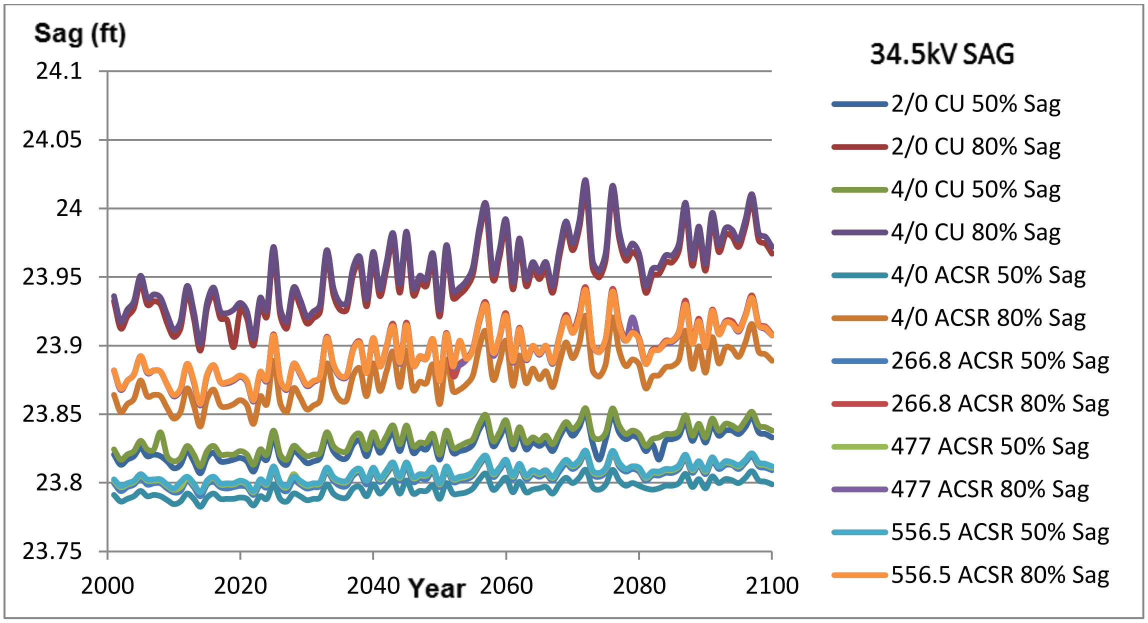

Figure 5.1: Transmission Line Sag for 34.5kV Conductors, IPCC Model A1b

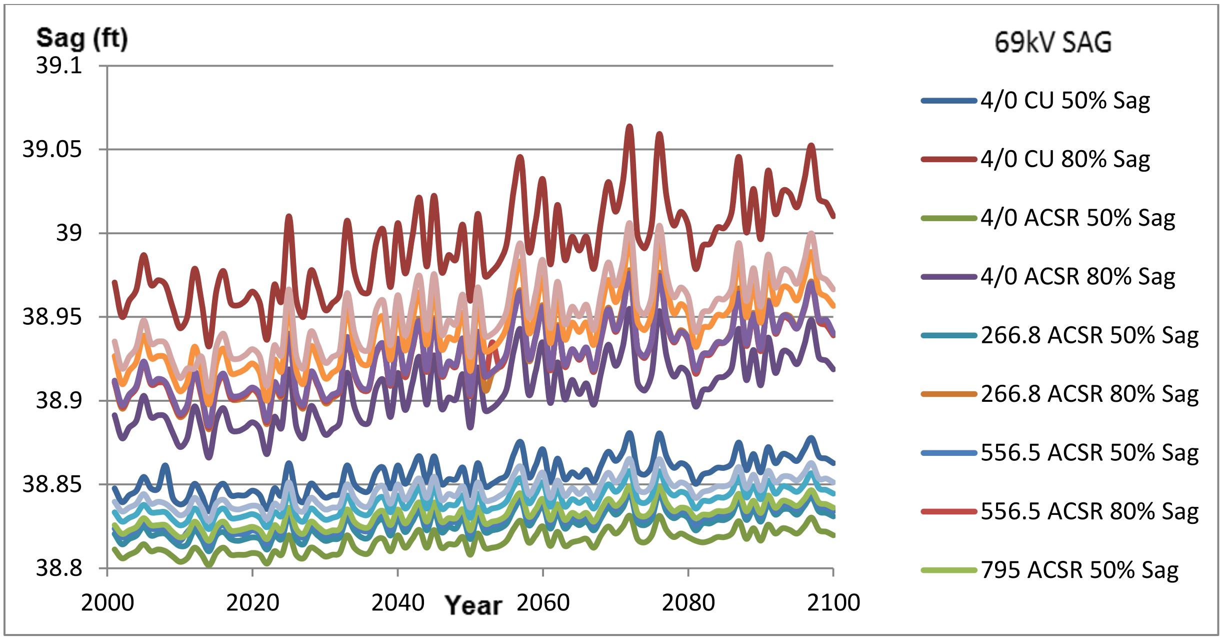

Figure 5.2: Transmission Line Sag for 69kV Conductors, IPCC Model A1b

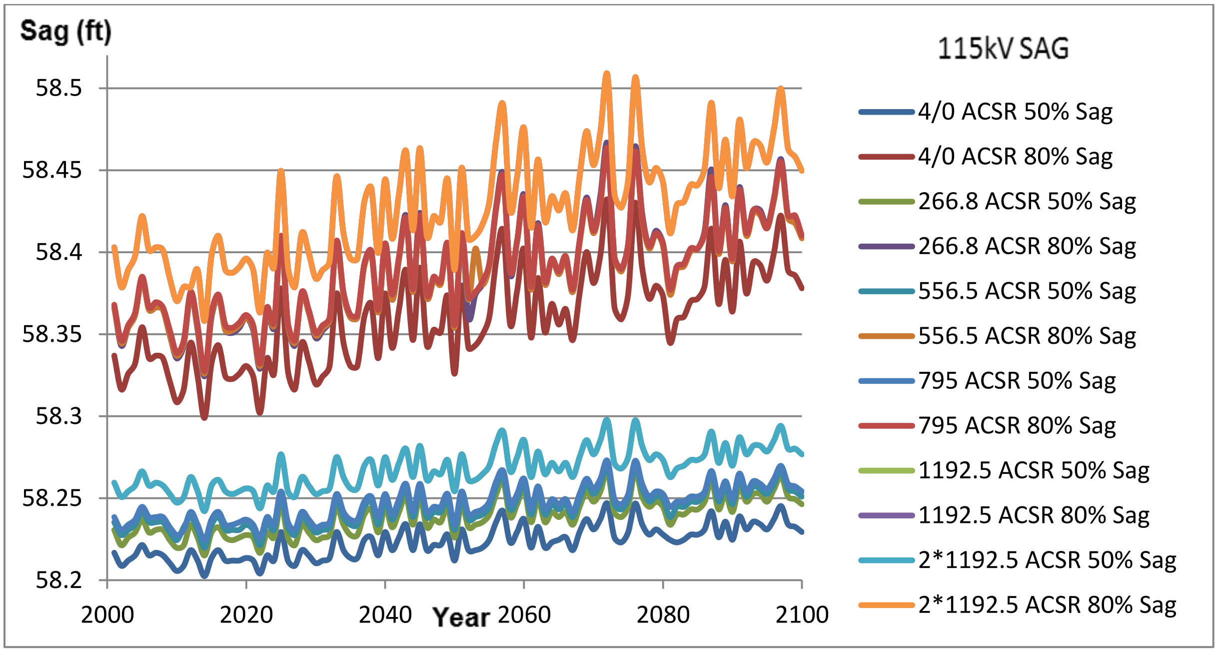

Figure 5.3: Transmission Line Sag for 115kV Conductors, IPCC Model A1b

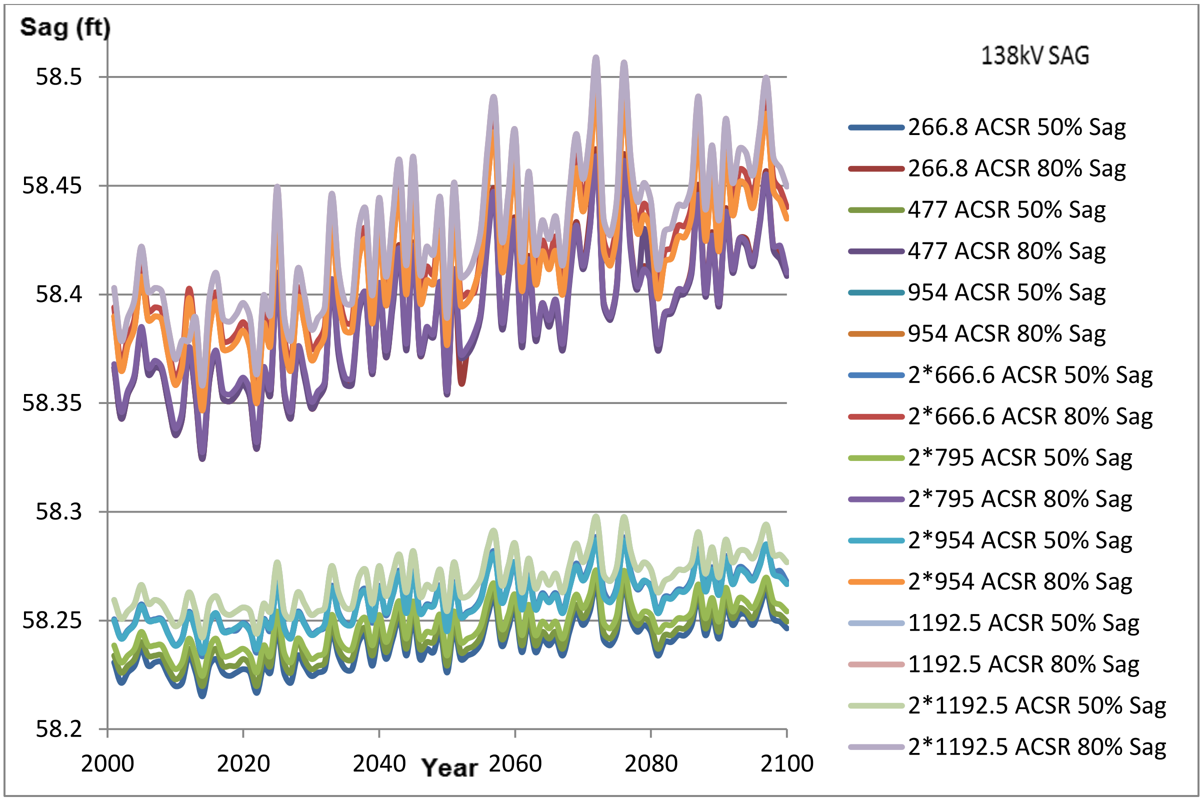

Figure 5.4: Transmission Line Sag for 138kV Conductors, IPCC Model A1b

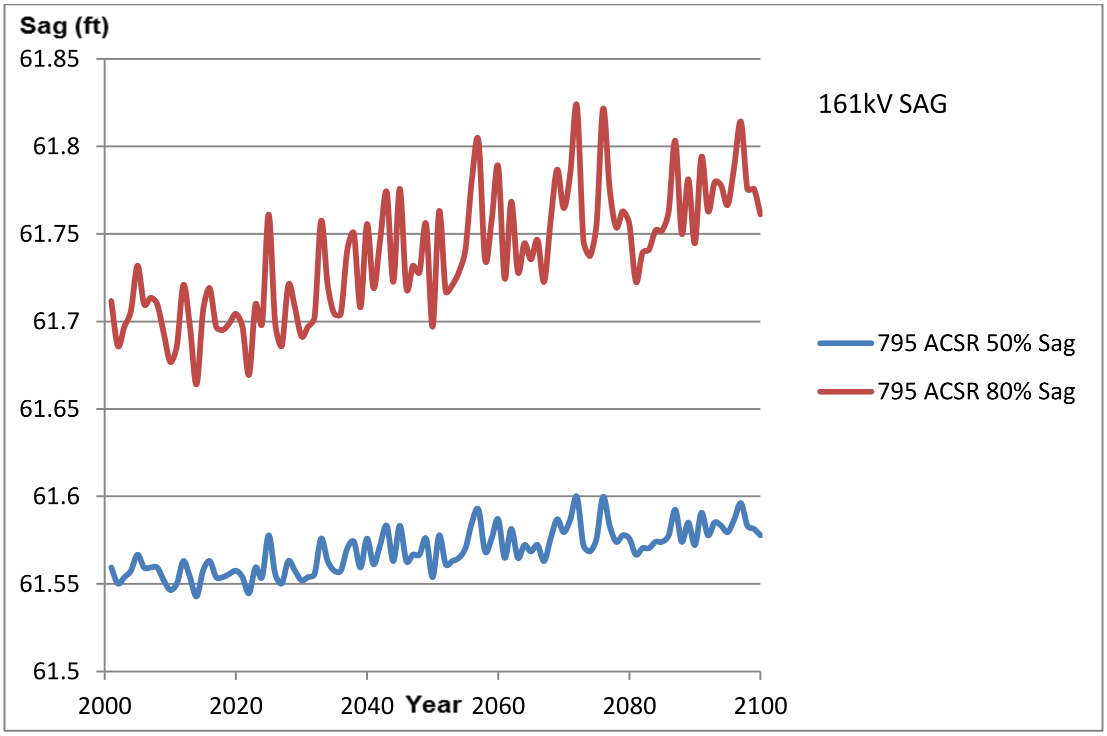

Figure 5.5: Transmission Line Sag for 161kV Conductors, IPCC Model A1b

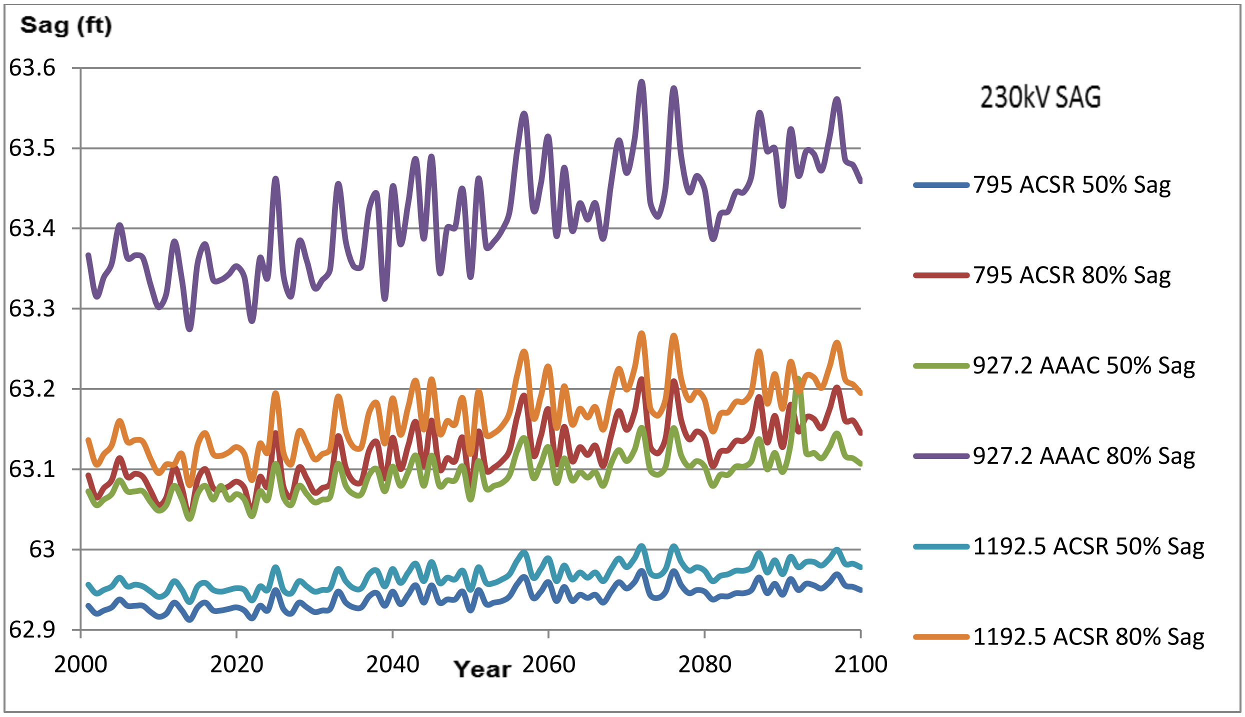

Figure 5.6: Transmission Line Sag for 230kV Conductors, IPCC Model A1b

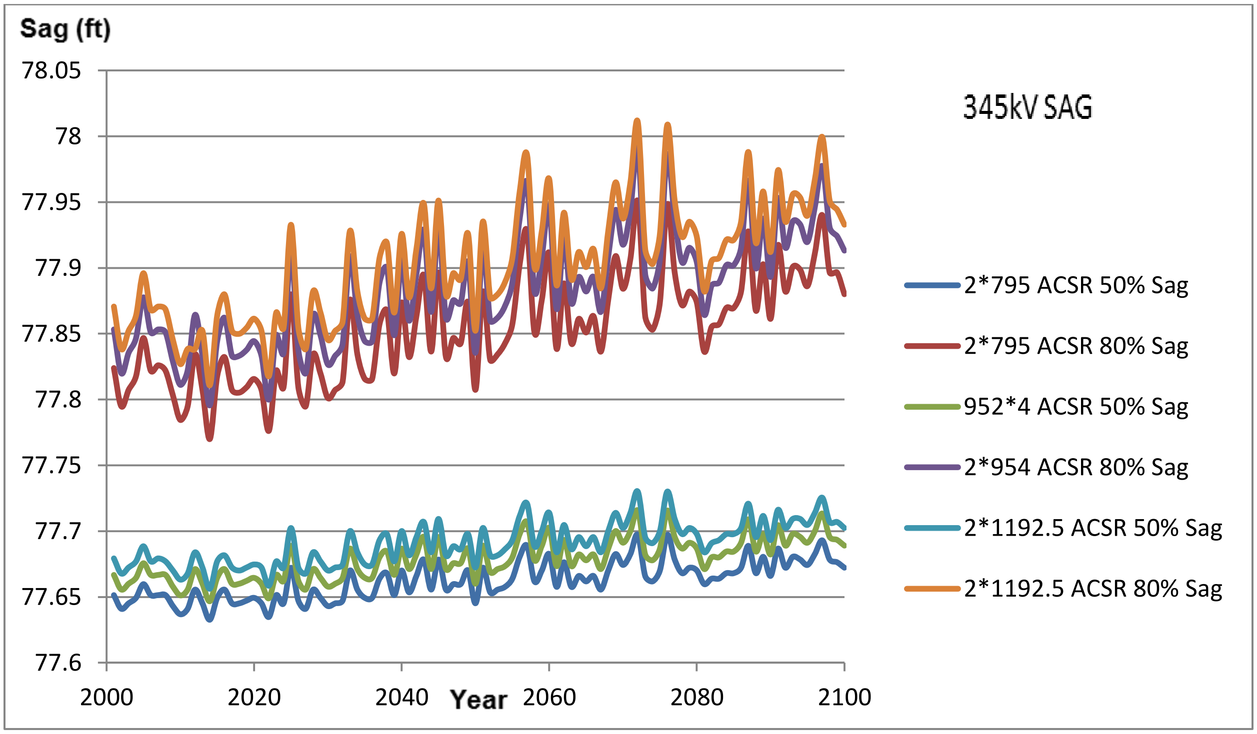

Figure 5.7: Transmission Line Sag for 345kV Conductors, IPCC Model A1b

Note that since Figures 5.1-5.7 used climate data from model A1b, it is seen that the plots seem similar to Figures 4.1 & 4.4 which also used model A1b. But since the voltage level of the conductors in each plot is different, the magnitudes differ accordingly.

Similarly, the plots, figures 5.8-5.14, based on model A2 are also similar to figures 4.2 & 4.5 and differ from the plots based on model A1b.

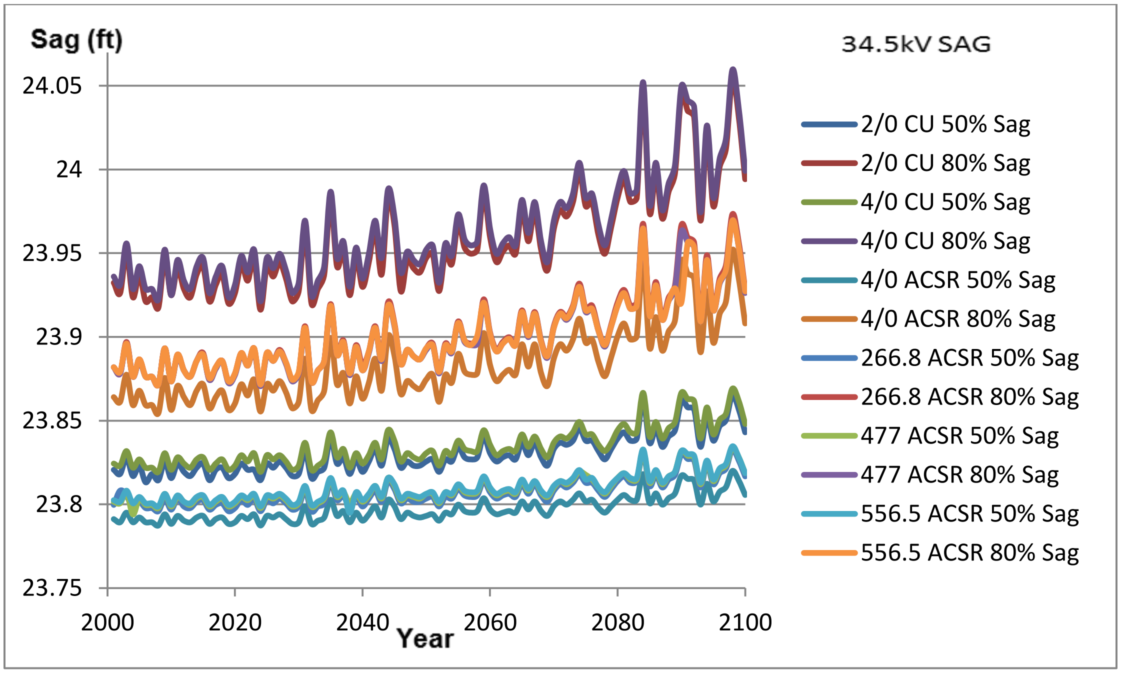

Figure 5.8: Transmission Line Sag for 34.5kV Conductors, IPCC Model A2

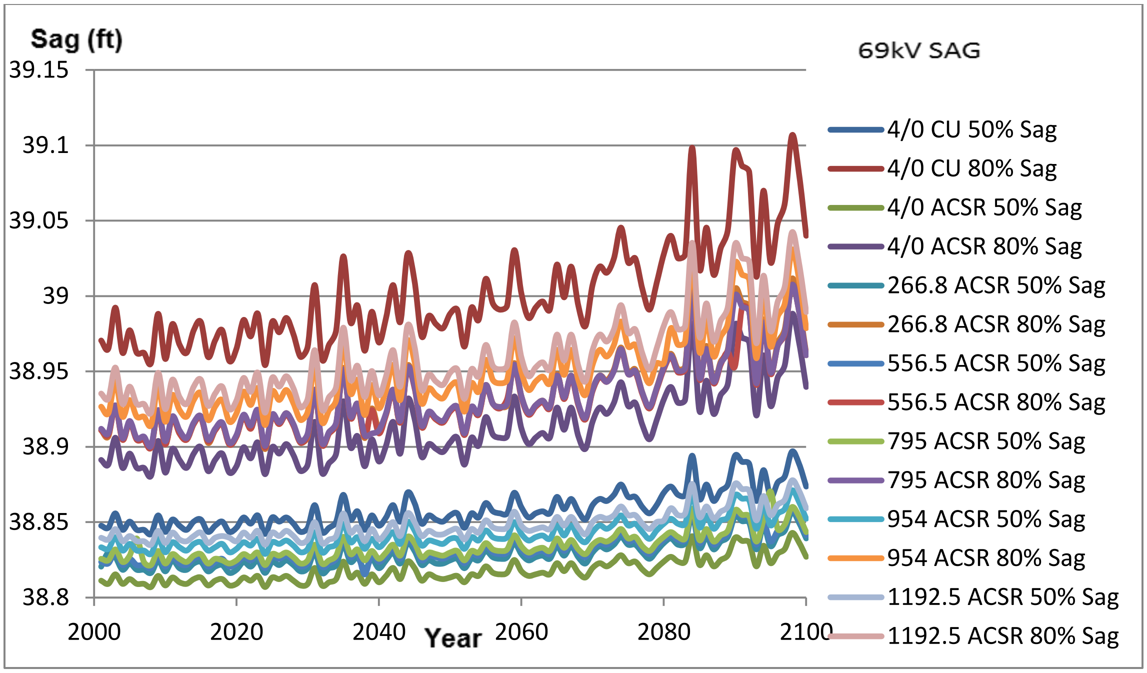

Figure 5.9: Transmission Line Sag for 69kV Conductors, IPCC Model A2

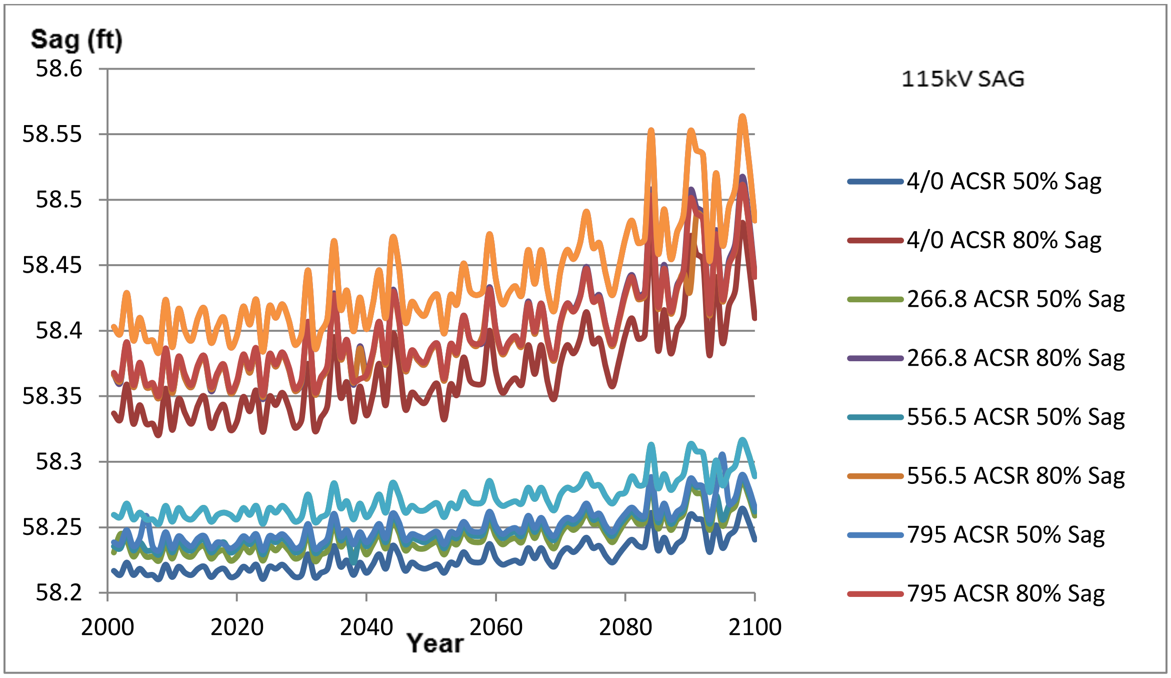

Figure 5.10: Transmission Line Sag for 115kV Conductors, IPCC Model A2

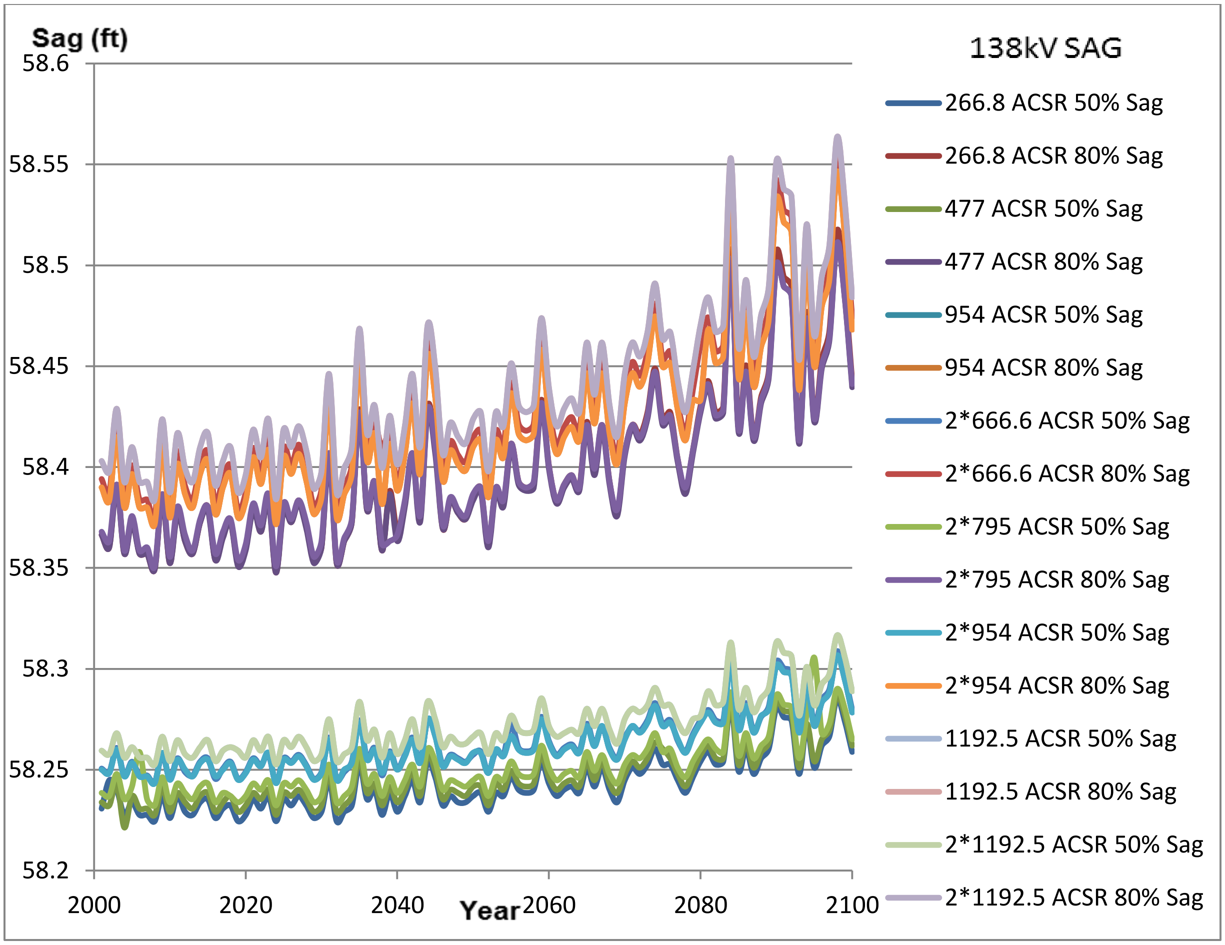

Figure 5.11: Transmission Line Sag for 138kV Conductors, IPCC Model A2

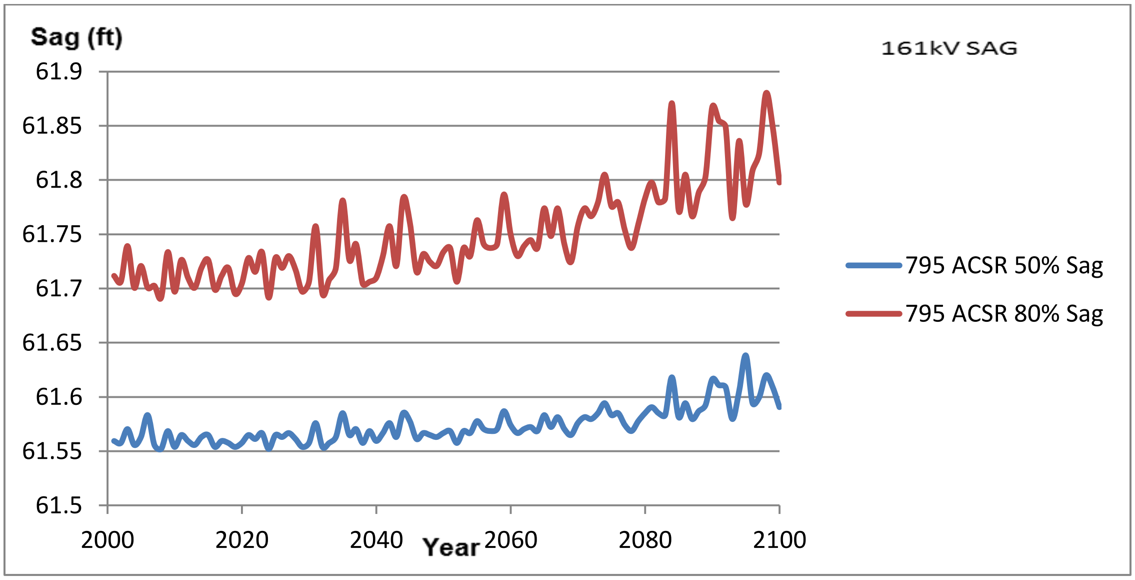

Figure 5.12: Transmission Line Sag for 161kV Conductors, IPCC Model A2

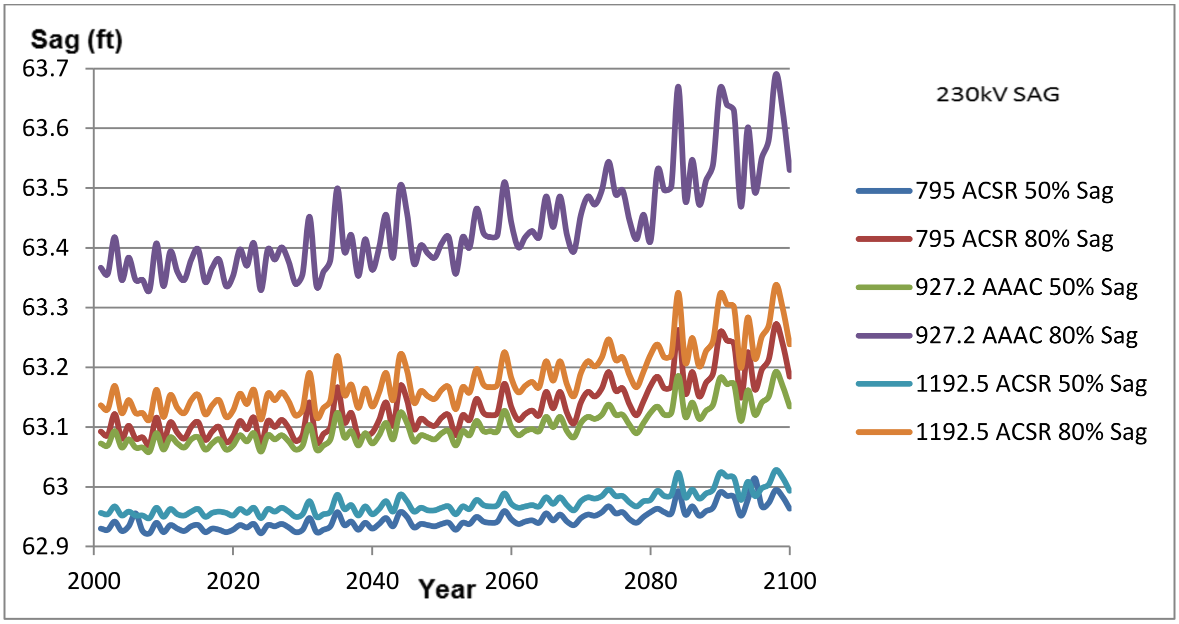

Figure 5.13: Transmission Line Sag for 230kV Conductors, IPCC Model A2

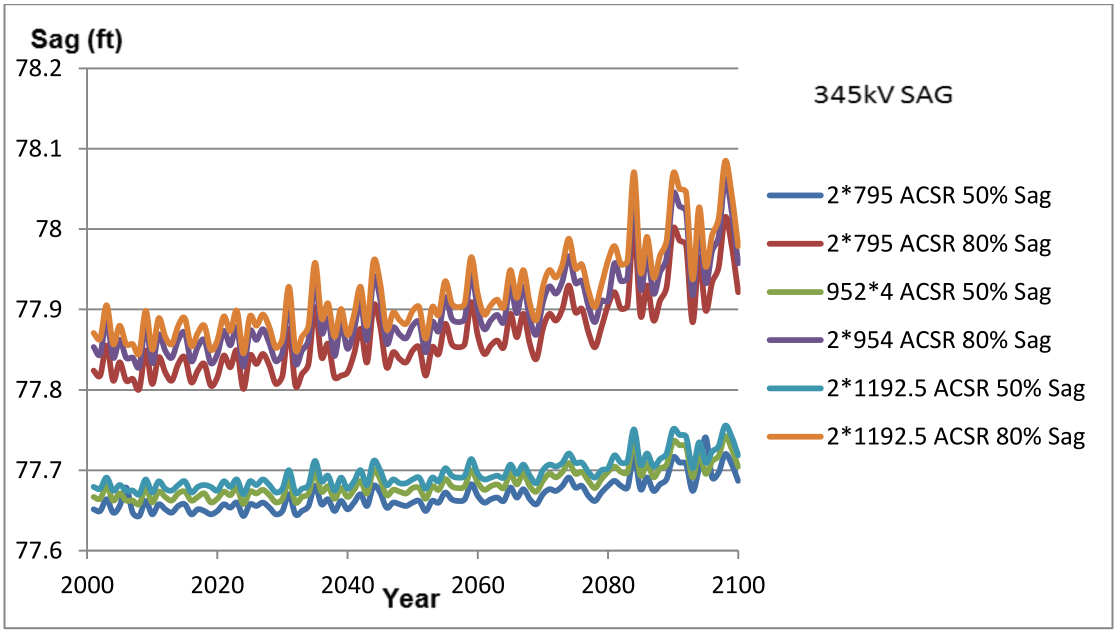

Figure 5.14: Transmission Line Sag for 345kV Conductors, IPCC Model A2

Similarly, the next set of plots, figures 5.15-5.21, look similar to figures 4.3 & 4.6 which use climate data from model B1. These plots are shown below.

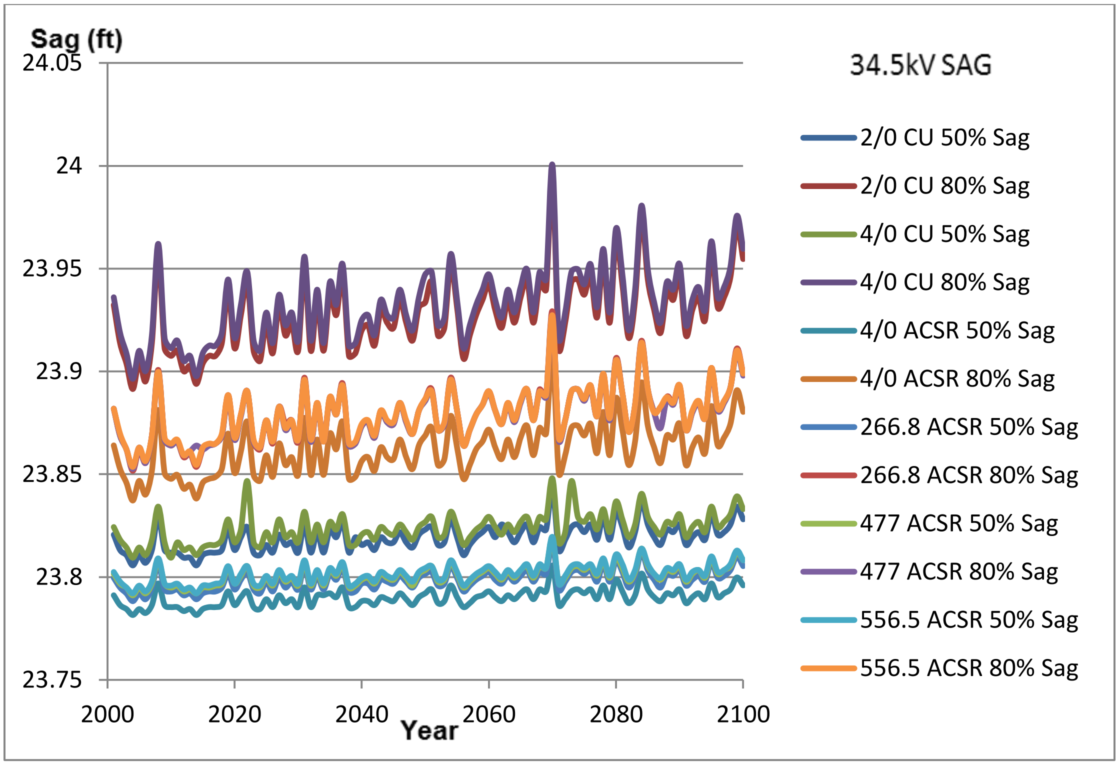

Figure 5.15 Transmission Line Sag for 34.5kV Conductors, IPCC Model B1

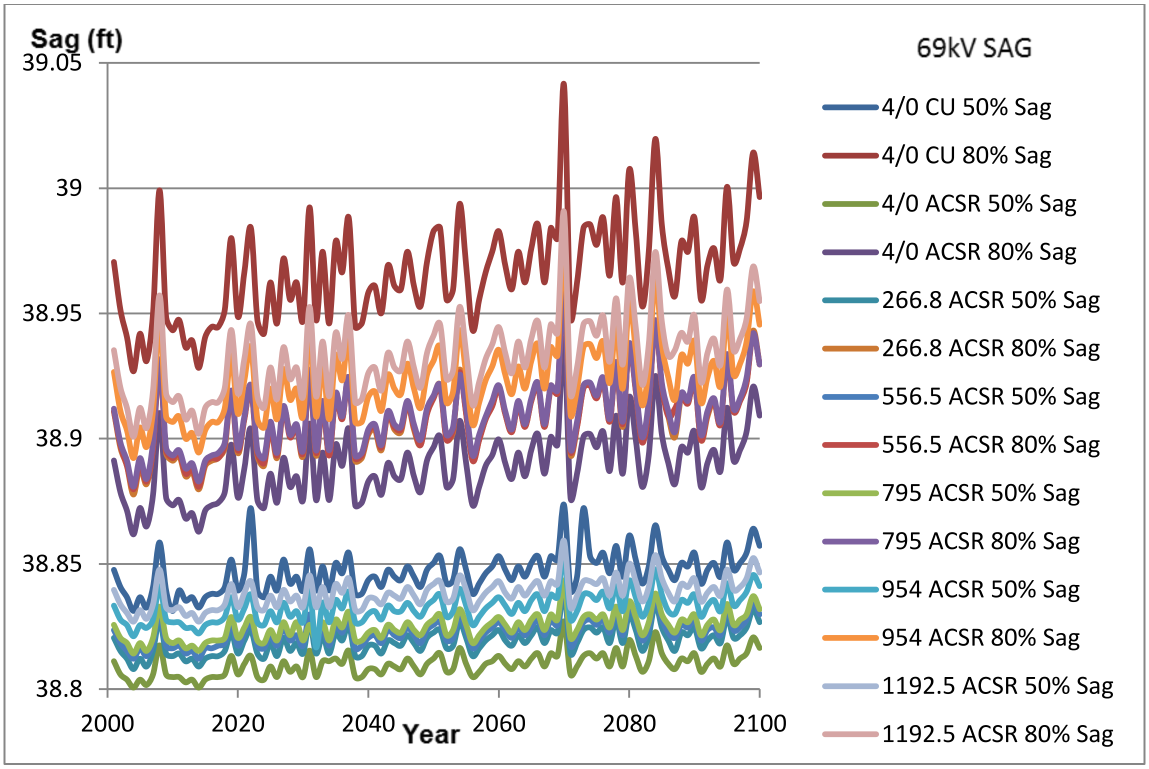

Figure 5.16 Transmission Line Sag for 69kV Conductors, IPCC Model B1

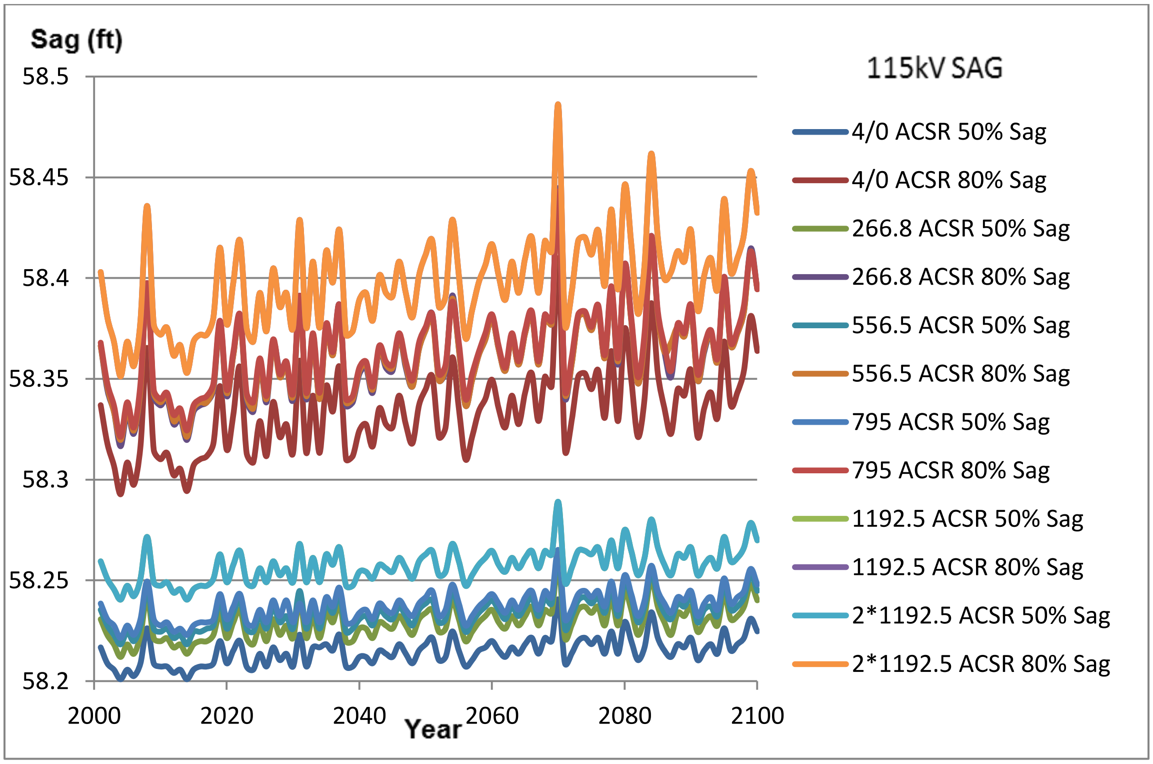

Figure 5.17: Transmission Line Sag for 115kV Conductors, IPCC Model B1

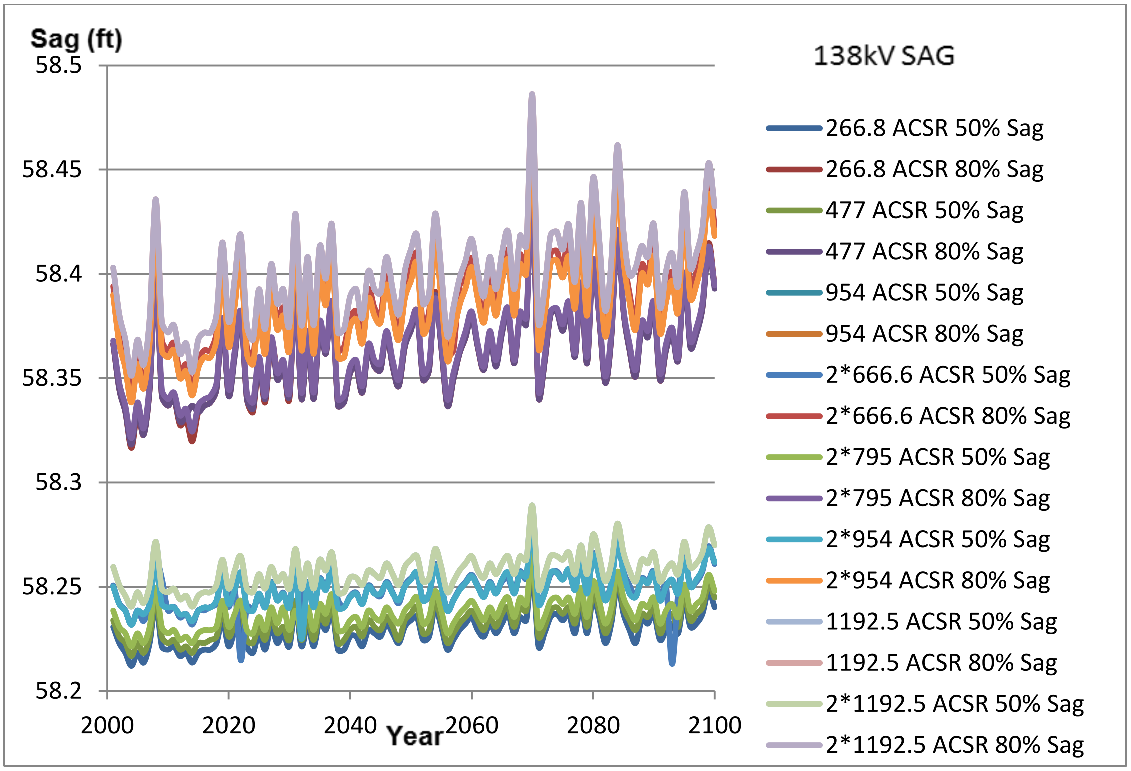

Figure 5.18: Transmission Line Sag for 138kV Conductors, IPCC Model B1

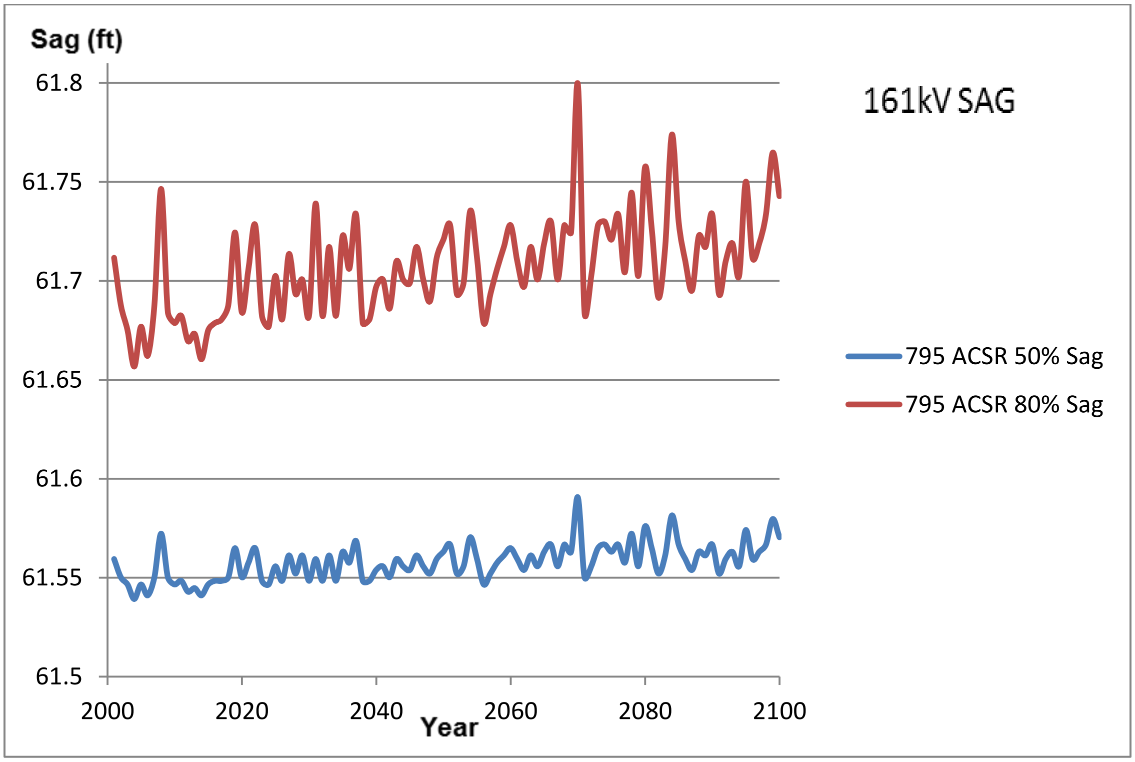

Figure 5.19: Time versus Sag Plot for 161kV Conductors. Model B1

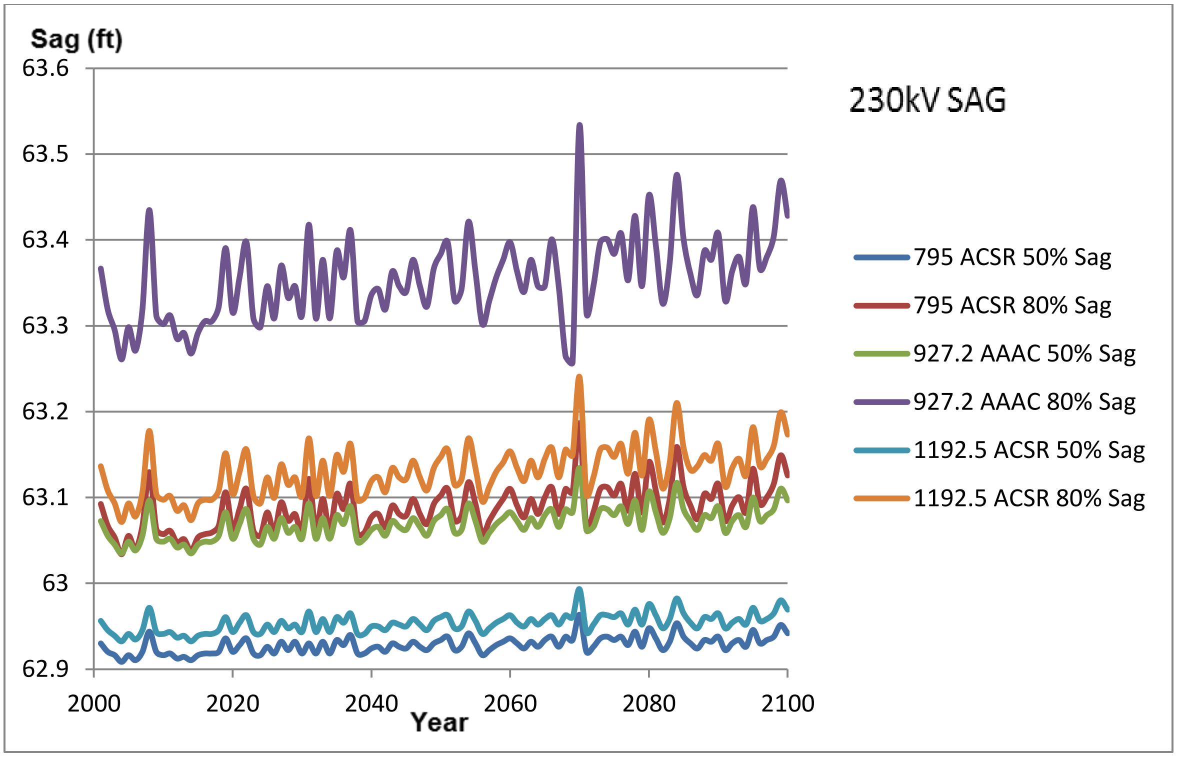

Figure 5.20: Transmission Line Sag for 230kV Conductors, IPCC Model B1

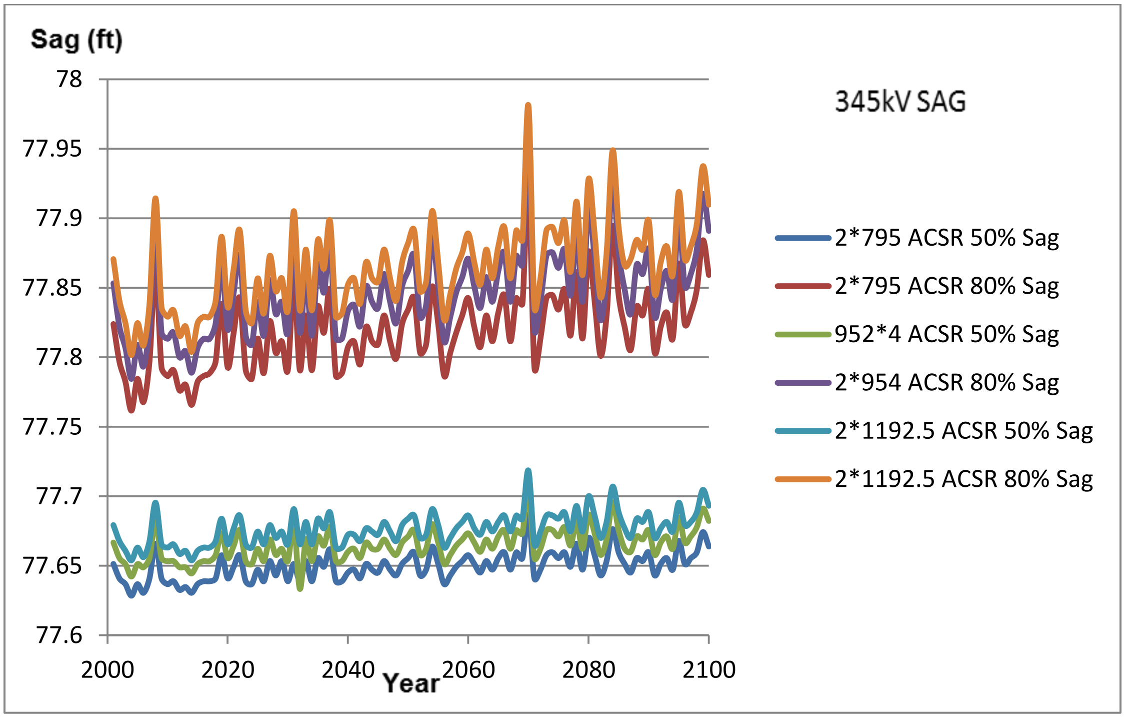

Figure 5.21: Transmission Line Sag for 345kV Conductors, IPCC Model B1

As seen from these plots as well as from Tables 5.1-5.3, the transmission line sag under normal operation during the 21st century ranges from less than an inch to almost two inches. According to the National Electrical Safety Code (NESC) published by IEEE [24], clearance buffers are usually 2.5 feet for voltages at 115kV or lower and 5 feet for voltages at 138kV or higher. Depending on the height of the transmission line poles and the voltage rating, the lines will be strung at their appropriate height taking into considerations a variety of factors such as terrain, climate, environment etc. But considering ideal conditions (20°C, level spans) and temperature being the only parameter that determines the electrical demand, the sag values obtained through the calculations in the project plainly show that transmission line sag is not significant enough to warrant further consideration when planning or constructing infrastructure in the future.

CHAPTER 6

CONCLUSION

The goal of this project was to demonstrate that a relationship between global warming and transmission line sag exists. The plots in chapter 5 plainly show that there is in fact a direct relationship between them and that the values obtained will affect future construction of transmission line infrastructure. In this respect the model developed is a reasonable explanation and proof that this relationship exists and needs to be considered in the planning and construction of transmission line infrastructure. However, it is only the tip of the iceberg for this topic.

Since the project is just a starting point on which to build, a lot of factors that affect the parameters which were calculated were neglected for simplicity sake. The sag calculated in the project is only intended as an estimate to demonstrate its relationship to global warming and the direction in which it is trending. These values cannot be used to everyday stringing purposes. For instance, resistance of a conductor changes with change in ambient temperature and current loading. But only ideal rated climate conditions were considered. This would change the entire scale of the project and the methodology needed to arrive at a solution. It would also ensure greater accuracy and be closer to real life conditions.

Another factor not considered is that of voltage drop. Voltage drop are usually seen in the range 5-7% over the entire length of the line. But in the project only single span lengths were considered. Hence voltage drop was neglected.

Another aspect which limited the accuracy and real life applicability of the transmission line sag calculations was the climate data used. Presently, long term climate models are still in developmental stages (see details in chapter 7) and the technology and research used to predict and generate climate data is still in nascent stages. More progress and development is needed to improve the accuracy of these predictions. Until then, the model can only be used as an accurate projector of trends and not detailed values. As a result it is only used as such in the project.

As stated earlier, since this project only examines the relationship between global warming and transmission line sag, it does not consider the physical ramifications of the increase in sag on the current transmission line infrastructure. This is another factor that will shape the way infrastructure should be constructed and the materials used in construction. An adaptation plan will need to be formulated to ensure that power transmission is not affected by global warming. Some of the solutions include turning to "superconducting" materials or ceramic core conductors which greatly reduce transmission losses and hence transmission line sag (see 7.7 for more details). However, either of these solutions are expensive to implement and maintain. Another solution is to increase underground transmission. But again these lines are difficult to access for repairs & maintenance and expensive to lay.

In spite of these limitations, the project was successful in creating a model that could reasonably demonstrate, and to some extent quantify, the relationship between global warming and transmission line sag. As a result, it provides a reasonable estimate of this relationship based on ideal conditions and existing industry knowledge.

CHAPTER 7

FUTURE WORK

The project was able to successfully demonstrate that there is in fact a direct relationship between global warming and transmission line sag. However, the model itself is intended as the first step in order to establish sag as another factor to consider when trying understanding how global warming affects the power grid. As a result, this topic warrants further research.

7.1 Advanced GCM’s

Climate modeling is still in its infant stages with relatively few players in this very important market. In addition it would be beneficial, if it is possible in the future, to run separate simulations for the project specifically as opposed to using data from previously simulated runs. With progressing technology and further research these GCM's will be able to deliver climate data projections with increasing accuracy. This increased accuracy will in turn help engineers analyze and predict how global warming affects the power grid with greater accuracy also.

There are other parameters that also need to be considered when choosing a potential GCM's factors such as population increase, exponential growth in power demand in emerging markets due to improving economic conditions and rural electrification initiatives which in turn contributes to rising GHG concentrations and hence global warming. But currently most GCM’s base their projections on the current rate of GHG concentration increase.

7.2 Conductor Creep

When transmission line sag occurs over a long period of time for a particular conductor, it causes a small amount of inelastic elongation known as Conductor Creep. This creep only increases as time progresses eventually causing the conductor to permanently hang dangerously close to the ground and violating clearance limits. In addition to clearance issues, conductor creep also decreases the life of the conductor which leads to a premature need for replacing the line.

7.3 Non Ideal conditions

In this project, a lot of the factors that affect transmission line sag have been ignored. For example, sag calculations for only level spans were performed. As a result the methodology detailed in this project is location specific and not universally applicable. For instance, in northern California a lot of transmission lines traverse very hilly areas which have high slopes making the current project inapplicable to such terrains.

Also not considered were ice and wind loading. The amount ice on a particular transmission line affects sag calculations since ice acts as a weight which pulls the transmission line down even further. This added weight increases conductor creep, which decreases the life of the conductor, and leads to clearance issues.

Wind loading is another factor when coupled with conductor sag seriously affects the system's reliability. When a conductor sags, the tension with which it was strung across a span, decreases. As a result, the requisite amount of wind blowing in a certain direction could cause each phase of the transmission line system to flap about and risk contact with adjacent conductors, which could cause an outage in that line. These factors need to be studied from a reliability perspective and assessed if global warming significantly affects the transmission system's reliability in the long run by potentially increasing the occurrence of wind and ice related transmission line power outages.

7.4 Geographic Locations

The geographic location affects also how the problem of sag needs to approached and addressed. In most regions of temperate or warm climates, sag is an issue mostly during the summer due to increased loads and in the winter due to ice/ wind loadings. However, in Finland, electricity demand reaches its peak during winter and is considerably lower during the summer months. Hence ice and wind loading become the primary issues to consider. Sag research for such climates would be valuable when conducting long term research about transmission line infrastructure planning.

7.5 Loss of Ampacity

As discussed earlier, ampacity is the maximum amount of current the conductor can carry. When transmission lines are regularly overloaded in hot ambient temperatures, the ampacity of these transmission lines decreases resulting in a decrease in system efficiency. This would be another parameter that would be affected by global warming since changing temperatures causes changes in amapacity levels.

7.6 Relationship between Sag and Line Losses

Another interesting and valuable topic of research would be exploring if there is a significant relationship between transmission line sag and transmission line losses.

The results of research on this topic could greatly affect future planning of transmission line infrastructure.

The starting point of this research would be the resistance and temperature relationship shown in equation 7.1.

$$R = R_0\,[1 + \alpha(T - T_0)]$$

Where T_0 is the reference temperature at which α is given , T is the current temperature of the conductor, R is the resistance at the current temperature, R_0 is the resistance of the conductor at reference temperature T_0, and α is the temperature coefficient of resistance for the conductor material. Therefore, using this relationship it can be possible to model a relationship between sag and line losses and ultimately determine if global warming also significantly affects transmission line losses.

7.7 Adaptation Plan

Another area that needs further research is developing an adaptation plan to mitigate these previously discussed effects of global warming that could occur on the transmission lines system. One area that could be explored, is the widespread use of super conductors with composite cores. These conductors have very high melting points and only undergo negligible sag when used in normal as well as emergency operation due to their significantly low coefficient of thermal expansion. One of the manufacturers of these super conductors, 3M [25], stated in the Oak Ridge National Laboratory Review that the sag in their conductors at 210°C is the same as that of a standard steel line at the rated operating temperature of 100°C

Another advantage of composite core conductors is the increased current carrying capacity. According to 3M [25] composite core conductors can carry 1.5 to 3 times the current of conventional steel-core, power-line cables at the same voltage. Testing done by 3M also shows that these super conductors can also withstand extreme heat, salt corrosion and extreme cold.

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