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Leveraging a Geographic Information System in Co-optimized Generation and Transmission Expansion Planning for Iowa

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Leveraging a geographic information system in co-optimized generation and transmission expansion planning for Iowa

by

Abhinav Venkatraman

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Electrical Engineering

Program of Study Committee:
James D. McCalley, Co-Major Professor
Chris Harding, Co-Major Professor
Lizhi Wang

Iowa State University

Ames, Iowa

2016

DEDICATION

I would like to dedicate this thesis to my parents, Gayathri and Venkat, for believing in me, for nurturing good values in me, for being pillars of strength and support, and for always being there for me. I would like to express my gratitude to my grandparents for their prayers and blessings, and to my family for their constant encouragement. I would also like to dedicate this thesis to all my friends who have been incredibly supportive at every point in my life.

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I would like to take this opportunity to express my heartfelt gratitude to those who helped me with various aspects of this research and in the writing of this thesis. First and foremost, Dr.James McCalley and Dr.Chris Harding for their constant support and guidance throughout the course of this research, and for spending many hours not only helping me navigate the nuances of expansion planning and ArcGIS, respectively, but also for their invaluable feedback and continuous encouragement which played a vital role in the successful completion of this research. I would also like to acknowledge the support of the Electric Power Research Center at Iowa State University in funding this research. This thesis wouldn’t have been possible without the contribution of Dr.Ali Jahanbani-Ardakani who coded the Co-optimized Generation and Transmission Expansion Planning software in GAMS and modified it to suit the requirements of this research, and also provided me with useful advice regarding several aspects of this work. I would like to thank Dr.Lizhi Wang for taking interest in this research and serving on my POS committee. Last, but certainly not the least, I would like to thank all my fellow students and industry members from the EPRC for their constructive feedback and comments during the course of this research.

ABSTRACT

With everyday lives becoming increasingly energy intensive, the need of the hour is to plan for the growing demand for clean energy in the future. This research project anticipates a very high wind penetration future for Iowa, and with it the necessity to upgrade or build transmission to transfer the energy to load centers in the east and south. Unlike the traditional planning approach which identifies generation and transmission system investment sequentially, a co-optimization approach identifies them simultaneously, yielding significant economic benefit. Interpreting the results of the planning process is crucial and the ability to visualize these results helps in better understanding of the plan. Thus, to support this approach, a Geographic Information System (GIS) is used to select feasible sites for wind farms, and to efficiently communicate complex generation and transmission expansion planning investment results which are co-optimized.

CHAPTER 1. OVERVIEW

1.1. Introduction

The state of Iowa is one of the largest producers of wind energy in the country, and if the current pace of growth in wind turbine installations continues, it might well be on its way to becoming almost fully self-sufficient using wind energy alone in the next twenty years. With Iowa already being an energy-surplus state, such a future will bring with it the necessity to construct transmission infrastructure to move this clean energy towards the load centers. Hereafter, a process for planning and visualization of generation and transmission infrastructure in Iowa is described, assuming a high wind penetration future in which at least 20 GW of wind capacity is installed.

In this chapter, the main motivations for the project are outlined, including compelling reasons to use co-optimization in the planning process and the importance of being able to visualize its outcome. A brief literature review is presented, followed by a description of the approach to the planning and visualization process. In Chapter 2, a method developed to identify candidate wind farm sites using GIS is described. In Chapter 3, co-optimization is introduced and its application to generation and transmission expansion planning is illustrated using the Iowa power system as an example. System topology, assumptions and formulation are discussed, followed by an overview of the results. In Chapter 4, a method to visualize the planning results using ArcGIS is described along with its features, and results of the co-optimized generation and transmission planning carried out for Iowa are presented visually. In Chapter 5, a study done to assess the value of transmission is presented. The study compares two scenarios for Iowa – one in which only generation expansion is allowed, and another in which both generation and transmission expansion is co-optimized. Chapter 6 provides a summary and conclusion of the thesis, and scope for future research is discussed based on the work done for this thesis.

1.2. Motivation

This research is motivated by the need to illustrate the use of co-optimized generation and transmission expansion planning for Iowa under a high wind penetration future (minimum 20 GW of wind nameplate capacity additions by 2036), and to identify related grid designs. To accomplish this, an industrial strength GIS software, ESRI's ArcGIS 10, is used since it provides visualization capability for communicating expansion plans in terms of the most cost-effective new generation and transmission investments.

1.2.1. Wind energy in Iowa and its future

Iowa's energy policies have for many years promoted green and environment-friendly sources of energy, confirmed by the fact that Iowa was the first state in the U.S. to adopt a Renewable Portfolio Standard (RPS) in 1983 [1].

Historically, Iowa relied on low-sulfur coal brought in from Wyoming to meet the majority of its energy needs. However, in the recent past, the meteoric rise of clean, non-polluting wind energy production in Iowa has reduced this dependence on coal – from 75.6% electricity generated using coal in 2006 to 53% in 2015 [2][3]. Towards the end of 2015, wind provided 31.3% of Iowa's total electricity generation, a larger share than any other state in the country, according to the U.S. Energy Information Administration [4]. It is also second in the country, after Texas, in total amount of electric energy generated using wind and in total generating wind capacity.

MidAmerican Energy Company, one of Iowa's largest electricity generation and utility companies serving almost two-thirds of Iowa, will have 4048.2 MW of installed wind capacity by the end of 2016, and has announced Wind XI, a $3.6 billion project that will add 2000 MW of wind generation capacity by 2018 [5][6]. MidAmerican is aiming at generating 85% of its energy from wind within the next five years, and dreams of delivering 100% renewable energy to its customers, giving us enough reason to believe that wind energy is on its way to becoming the largest single source of clean energy in Iowa [7]. Likewise, Alliant Energy has recently announced an additional investment into a 500 MW expansion of its wind fleet. Additional investment is occurring from other organizations [8].

The Consolidated Appropriations Act, 2016, extended the expiration date for the production tax credit (PTC) for the first 10 years of operation for wind facilities commencing construction by December 31, 2019 [9], albeit at a diminishing level starting from 2.3 cents/kWh in 2016 to 40% of that in 2019, after when it becomes zero. Developers and owners consider the PTC as a major incentive to build and operate wind farms since it allows them to bid and sell into the electricity market at very low prices compared to other generation technologies. In fact, the PTC allows wind producers to bid in and sell at negative prices at times, and still make a profit [10].

Today, 20 GW more of wind generation in the next 20 years is a significant increase; but it is both technically and economically feasible, as indicated by the U.S. Department of Energy’s Wind Vision study which articulates a vision to add close to 21 GW of wind generation in Iowa between now and 2030 [11].

According to a study by AWS Truepower/NREL, 78.32% of land in Iowa has a potential for gross capacity factor greater than 30%, with a wind energy potential installed capacity of over 570,700 MW [12]. Thus, the driving factor for this research is not the existing ~6300MW of wind generation capacity (8.4% of the total installed wind power capacity in the US), but the very high wind penetration future that Iowa could see in the next 20 years and the transmission infrastructure that would be needed to move much of this clean energy towards load centers in the east and south [4].

1.2.2. Necessity for co-optimized planning

To meet the energy needs of the future, investment in generation technologies alone is not sufficient. Expanding and reinforcing transmission infrastructure is equally important.

In the past, the electric power industry was traditionally in the form of vertically integrated utilities in which generation, transmission and distribution, all three were owned and operated by a single organization. With the breakdown of vertically integrated utilities into separate companies, it has become essential to ensure that capacity expansion planning for generation and transmission is done in an economically viable manner, especially in the present scenario where interaction between these companies is limited by FERC rules, and Independent System Operators, in their capacity as Regional Transmission Organizations, perform the function of coordinating regional planning studies.

Thus, instead of the traditional planning method of formulating a generation expansion plan first, followed by a transmission expansion plan, co-optimization of generation and transmission makes sense since it finds minimum cost solutions among all combinations of generation and transmission. It also enables the plan to anticipate how generation siting would respond to transmission expansion, and enables transmission planners to perform what is called ‘anticipative planning’.

1.2.3. Necessity for visualizing expansion plans

‘A picture is worth a thousand words’ is a famous English idiom, referring to the notion that the essence of a complex idea can be conveyed easily and more effectively using a single picture.

In the context of this project, expansion planning can result in spreadsheets with several thousands of rows that are difficult to analyze in a short span of time. Viewing expansion planning not as a predictive tool, but rather as an exploratory one, provides planners with a sense of what, where, when and how much generation and transmission to build or retire in order to arrive at conclusions and make decisions. Thus, in this project, ESRI’s ARGIS v10 is used to animate and visualize these expansion plans over the planning horizon.

1.3. Co-optimization and GIS Visualization in Existing Literature

This research builds on closely related work performed by a former graduate student, James Slegers, at Iowa State University in which resource to backbone transmission for Iowa was designed based on a 20GW wind penetration future and the existence of 765kV high capacity backbone transmission [13]. The results identified transmission designs to minimize investment and operational costs while satisfying reliability criteria, and a design process was developed and implemented. However, only wind generation was allowed to expand using a sequential generation and transmission planning process (co-optimization was not used), and no user-friendly tool was put in place to display the results visually. In this work, we have addressed these issues; in addition, relative to the work done in [13], we have used public data sources to improve the dataset representing the Iowa electric power grid. The said work also made an effort to identify optimal wind farm sites using MATLAB [14]. This project improves this process by using ArcGIS.

A white paper prepared for the Eastern Interconnection States Planning Council (EISPC) on “Co-optimization of transmission and other supply resources” lays a firm foundation for the discussion on and use of co-optimization for generation and transmission resources [15]. It also presents several numerical examples to demonstrate the benefits of co-optimization.

The Energy Systems journal, in its May 2016 edition, published a paper on ‘Co-optimization of electricity transmission and generation resources for planning and policy analysis: review of concepts and modeling approaches,’ which presents a good review of co-optimization as a concept, and provides an overview of approaches to co-optimizing transmission options, supply-side resources, demand-side resources and natural gas pipelines [16].

Co-optimized identification of infrastructure portfolios, including generation and transmission is one of the core capabilities of the National Energy and Transportation

Planning model (NETPLAN), among the earlier works in co-optimized generation and transmission planning [17].

To simplify the transmission topology and reduce computational burden, a ‘hybrid’ transmission model described by R.Romero et al. has been used in this project, and has been described in chapter 4 [18].

ArcGIS is a versatile software with multifarious capabilities, a few of which have been used in this project. Inspiration for conducting a feasibility analysis to identify candidate wind farm sites came from [19] in which J.Malczewski provides an overview of GIS-based land-use suitability analysis. ArcGIS has also been shown to provide useful tools for transmission design in the context of line siting [20].

1.4. Approach to the Planning and Visualization Process

The approach to the planning and visualization process is essentially a four step process, outlined in Figure 1.1.

Step 1. Identify factors which affect wind farm siting and using the GIS suitability analysis tool developed for this project to generate a raster of suitable wind farm sites.

Step 2. Identify candidate wind farms from the raster generated in Step 1.

Step 3. Provide these candidate wind farms as an input to the Co-optimized Generation and Transmission Planning software (CGT-PLAN), along with the Iowa system topology, cost data and assumptions.

Step 4. Visualize the result of CGT-PLAN using ArcGIS.

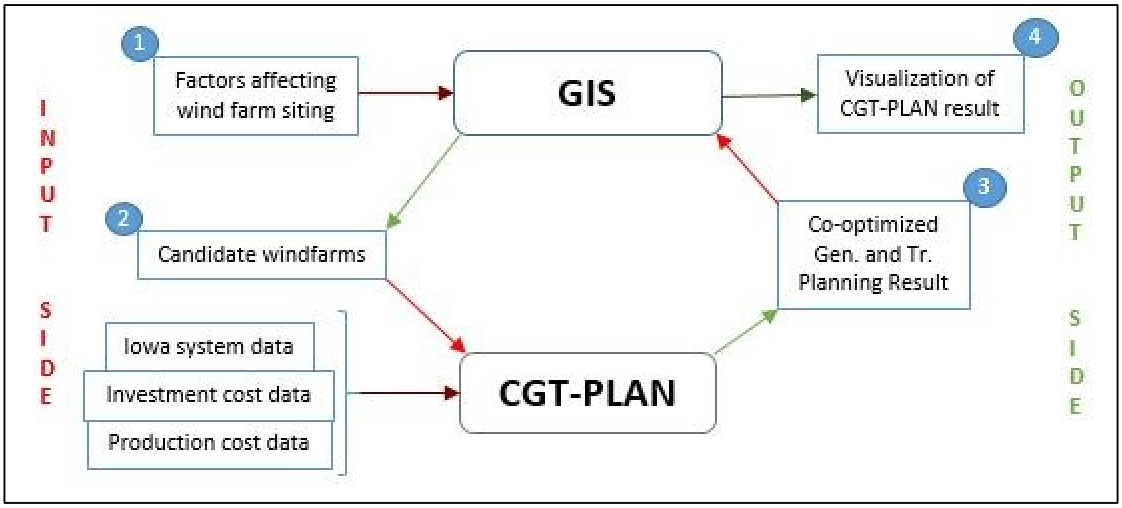


Figure 1.1 Planning and visualization process overview

CGT-PLAN is a software developed by Dr. McCalley's research group at Iowa State University within an optimization environment called GAMS, using a CPLEX solver. It has been adapted according to requirements for the Iowa power system by appropriately modifying or adding constraints to suit the modeling and expansion planning requirements.

The four steps outlined above will be explained in the next few chapters.

CHAPTER 2. SELECTION OF CANDIDATE WIND FARM SITES USING GIS

Predicting accurate locations for potential wind farm sites in Iowa is an important foundation for designing transmission infrastructure for a high wind penetration future. This can be achieved by utilizing the full capabilities of GIS (here we use ArcGIS 10) to substantially simplify the feasibility analysis for potential wind farm locations

2.1. Designing a Suitability Analysis Tool

A tool to execute the GIS process for conducting multi-criteria analysis of the feasibility of potential wind farm sites has been developed in such a way that input parameters can be easily modified to observe their effect on the final suitability raster.

2.1.1. Factors affecting wind farm siting

A typical GIS feasibility analysis requires a set of spatial factors that exert some influence on the final outcome. Each of these factors provides a feasibility value that represents the likelihood for the site to be a potential location for a wind farm, with respect to that particular factor. All of these feasibility values are then combined into an overall feasibility value for a location. Taking cues from [14], the following factors have been taken into account with data obtained from the Iowa Department of Natural Resources (DNR) GIS database [21]:

- Land Cover – At 15m resolution, this map (Figure 2.1) classifies the type of land use based on the attributes shown in Table 2.1. A 2009 report by NREL on 'Land-use requirements of modern wind power plants in the United States' was used as reference to decide which type of land cover/terrain can be used to build wind farms [22].

Table 2.1 Feasible and infeasible land cover types

Attribute	Building of wind farms allowed?
Unclassified	No
Water	No
Wetland	No
Bottomland Forest	No
Coniferous Forest	No
Deciduous Forest	No
Ungrazed Grassland	Yes
Grazed Grassland	Yes
Planted Grassland	Yes
Alfalfa/Hay	Yes
Corn	Yes
Soybeans	Yes
Other Rowcrop	Yes
Roads	No
Commercial/Industrial	No
Residential	No
Barren	Yes

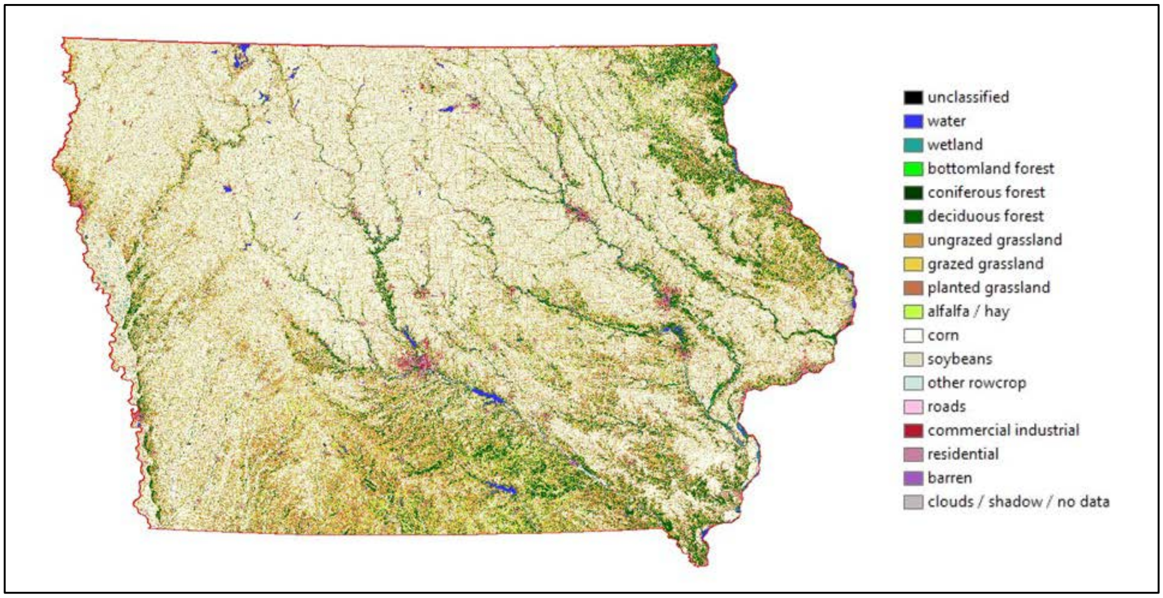


Figure 2.1 Land Cover raster

- Cities – Wind farms must be built outside city limits (Figure 2.2).

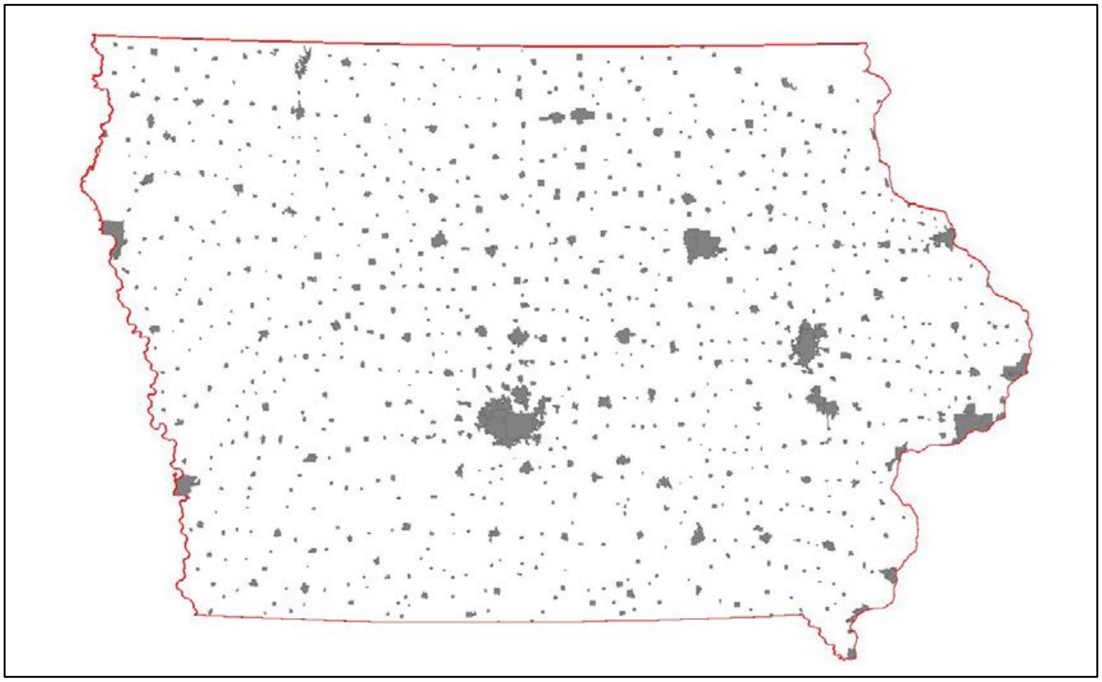


Figure 2.2 Cities raster

- Conservational and Recreational Land – Wind farms are often barred from being constructed in protected lands by pertinent state regulations. This map contains land reserved for conservational purposes or public recreation (Figure 2.3). Often, these lands require a buffer zone around them where construction is prohibited.
- Airports – The Federal Aviation Administration (FAA) requires that any structure taller than 200 feet in height seek its approval prior to construction due to height restrictions within a certain radius of airports, with restrictions varying with the length of the runway (Figure 2.4). Usually, the area within a radius of 5000 feet of a heliport, 10,000 feet of a small airport and 20,000 feet of a large airport is out of bounds for installing wind turbines.

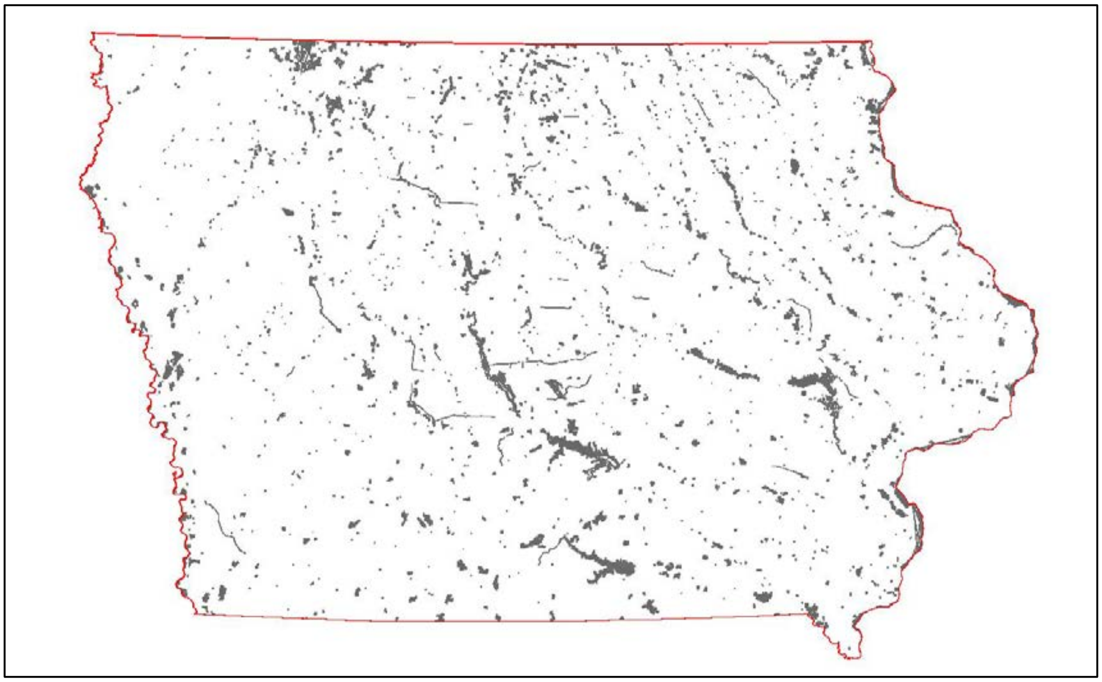


Figure 2.3 Conservational and recreational land raster

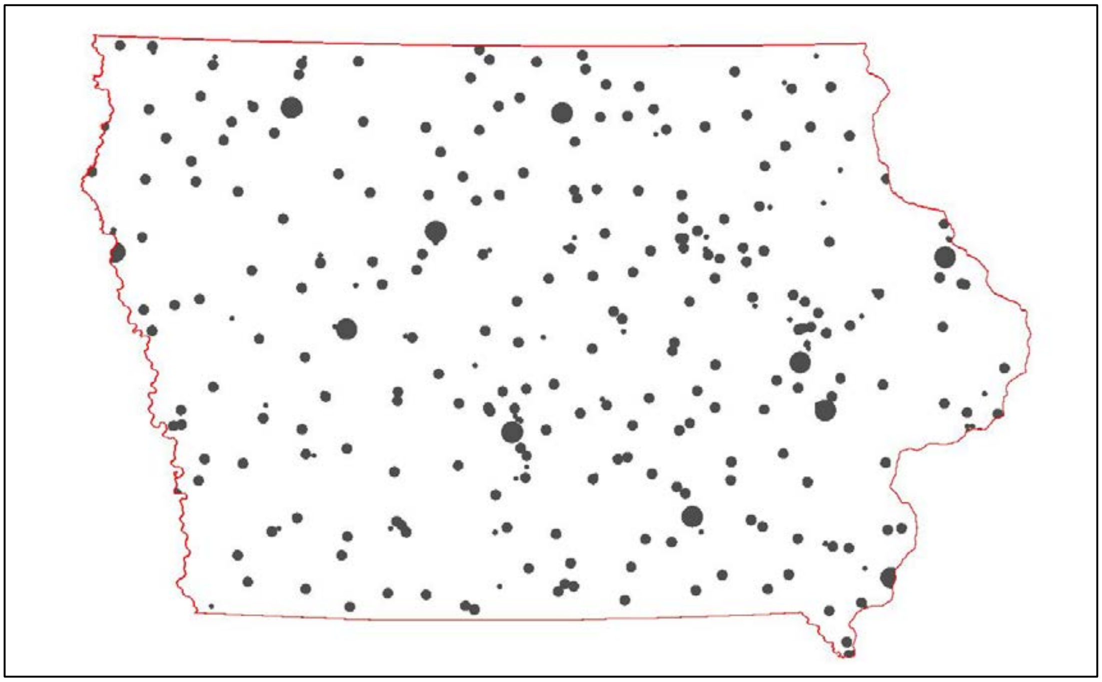


Figure 2.4 Airports raster

- Interstates and Highways – A setback of approximately twice the total height of a wind turbine is required from interstates and highways (Figure 2.5).

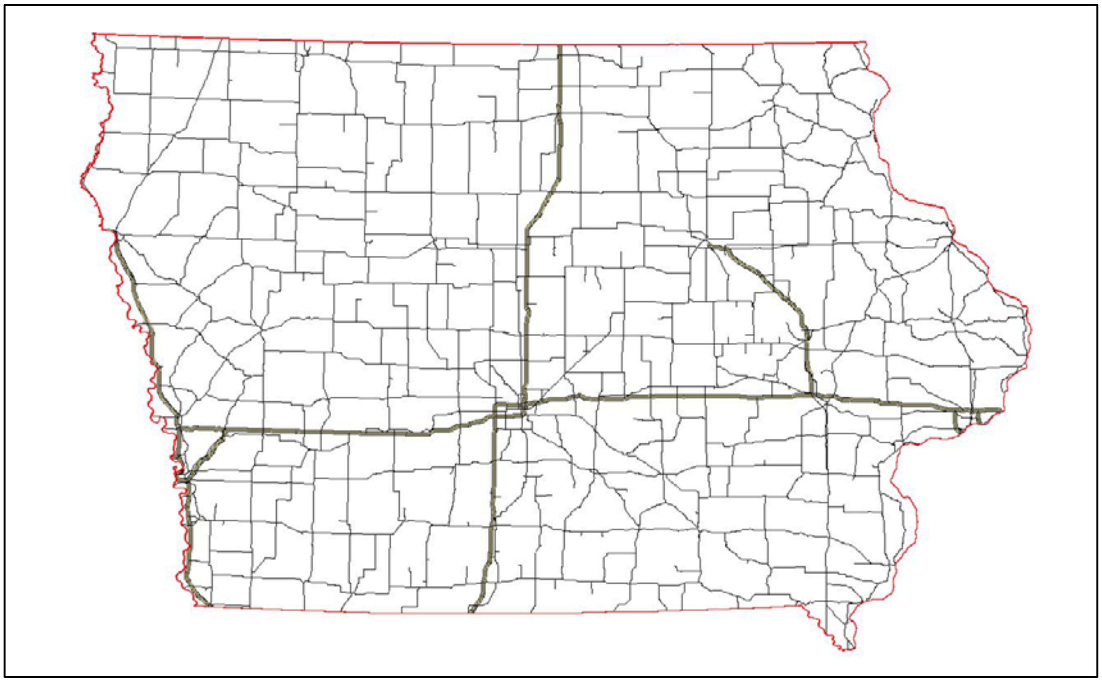


Figure 2.5 Interstates and Highways raster

- Existing and planned wind farms – The USGS Onshore Industrial Wind Turbine Locations data (through March 2014) was used to identify existing wind farms in Iowa (Figure 2.6), since the space occupied by these wind farms cannot be used for setting up new ones [23].

The issue of bird and bat fatalities is often taken up during discussions on the environmental impacts of wind turbines. The 2009 Eagle Permit Rule requires an application for eagle take permits for wind farms, which is an important step towards mitigating the risk to eagles [24]. Thus, an effort was made in this project to include bald

Figure 2.6 Existing wind farms raster

eagle habitats as one of the factors affecting wind farm siting. However, the American Wind Energy Association reported that wind farms impact very few eagles – less than 2% of all human-caused golden eagle fatalities and only a handful of bald eagle fatalities have been attributed to wind turbines [25]. It was thus decided not to include eagle habitats as a factor in this study, though in no way does this project intend to undermine the importance of eagle conservation and the need to take steps to reduce the risks associated with eagle takes due to wind turbines.

Availability of transmission is another crucial factor in deciding whether a wind farm should be built at a particular site. However, this factor has not been explicitly considered in this analysis since the factor is inherent to the co-optimized planning software – it decides whether generation should be built at a particular location based on the availability of transmission, and it also decides whether transmission should be built in order to site generation at a particular location.

2.1.2. GIS process for wind farm feasibility analysis

The technical process for obtaining a feasibility raster to identify probable wind farm sites is as follows:

1) Data collection: Raw raster data is collected for multiple factors influencing the siting of wind farms, as described in the previous section.
2) Normalization: All input data is normalized to a common binary scale using reclassification. Areas with absolute infeasibility are assigned zeroes, and those with potential feasibility to site wind farms were assigned ones.
3) Composite raster: A binary composite raster is obtained by performing a Boolean AND operation on all the reclassified input rasters. The blackened out areas represent regions which are absolutely infeasible for wind farm siting (Figure 2.7).

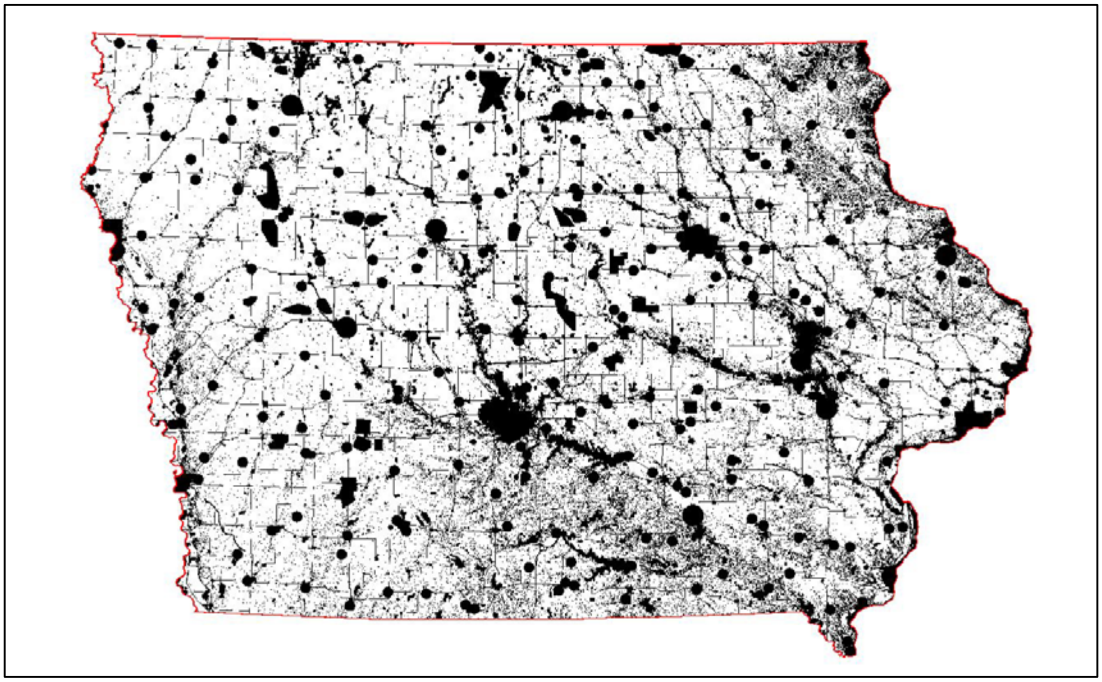


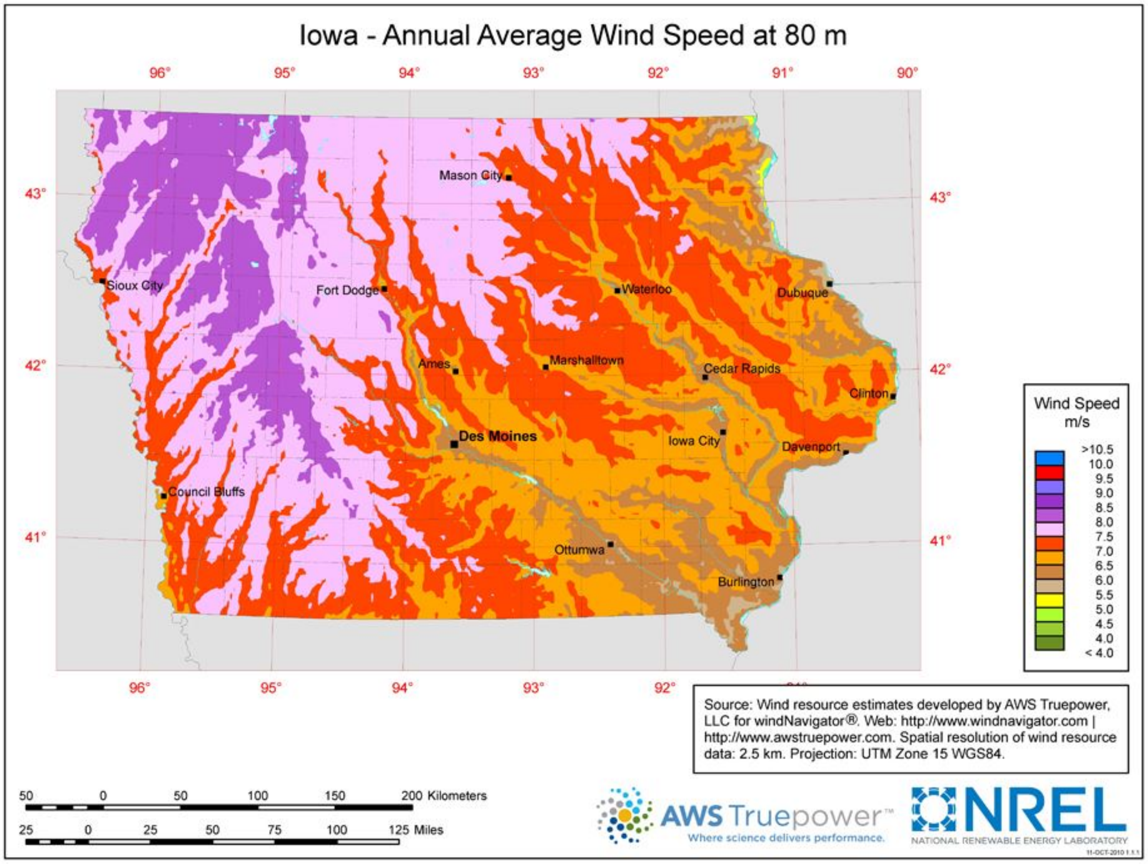
Figure 2.7 Binary Composite Raster

4) Final feasibility raster: By aggregating and masking the 80-meter wind resource map (Figure 2.8) for Iowa by AWS Truepower/NREL (in which areas with wind speeds greater than or equal to 7 m/s were considered feasible) on the binary composite raster, the final feasibility raster (Figure 2.9) is obtained [26]. The raster calculator available in ArcMap was used to compute the feasibility raster using the following formula:

$$(C\&W)*3 + C*2 + W*1$$

where C: Binary composite raster

W: Reclassified and aggregated binary 80m wind speed raster


Iowa - Annual Average Wind Speed at 80 m

Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: UTM Zone 15 WGS84.

Figure 2.8 NREL 80m Annual Average Wind Speed Map for Iowa

The final feasibility raster has been obtained for a target project size of 200 MW, assuming a cell size of 5mi x 5mi and an estimated capacity density of 8MW/mi^2, based on the typical size of wind farms [27].

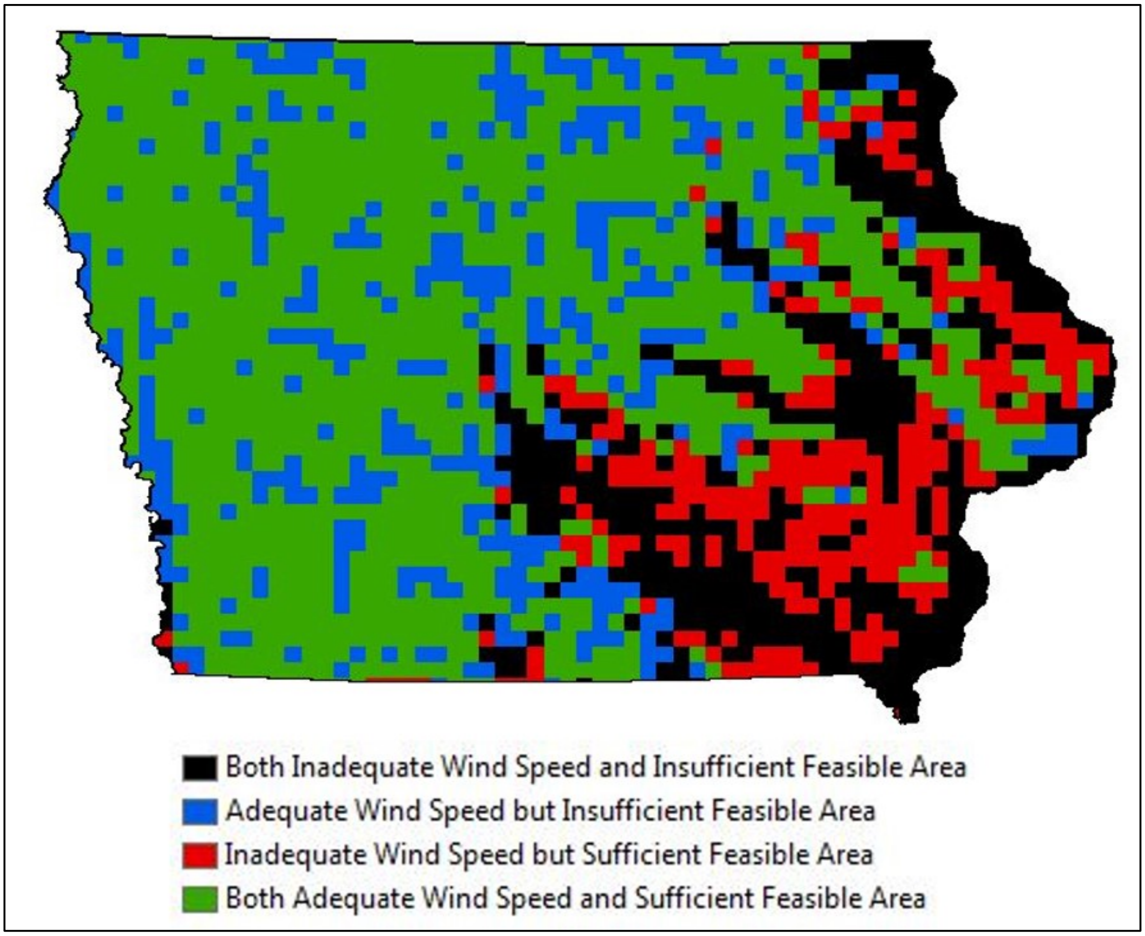


Figure 2.9 Feasibility Raster identifying feasible wind farm sites

2.1.3. Model using ArcGIS model builder

The process described above is tedious and time consuming if it has to be repeated multiple number of times to analyze how different inputs affect the result. Thus, it has been automated by developing a model in ArcGIS, allowing the user to make changes to the inputs in a convenient manner and producing a result within a few seconds. The model is shown in Figure 2.10.

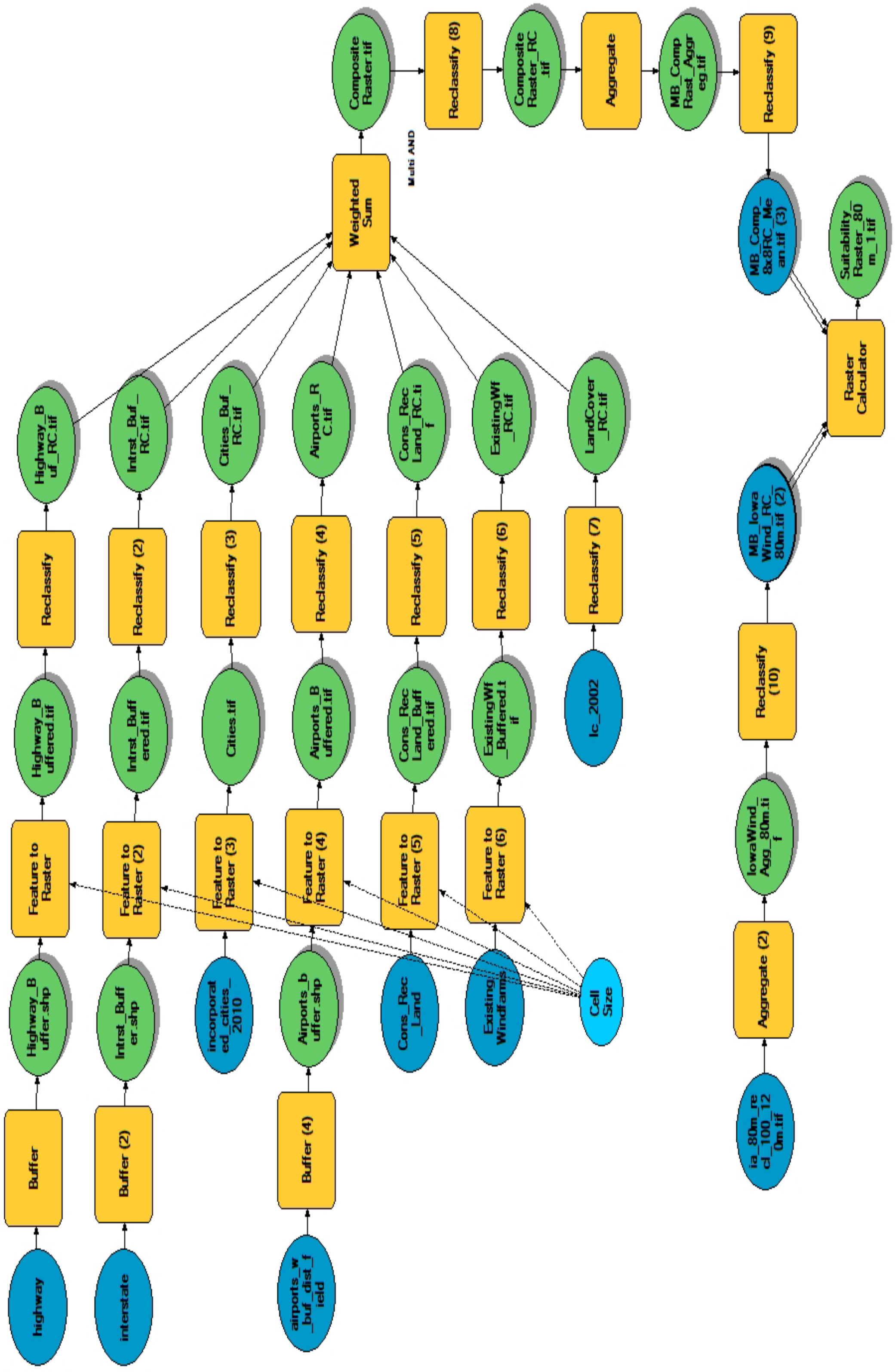


Figure 2.10 Suitability tool using Model Builder in ArcGIS

2.2. Candidate Site Identification

The GIS suitability analysis and the choice of candidate wind farm sites based on this analysis plays an important role as a data foundation for CGT-PLAN.

Based on the feasibility raster, wind farm candidates are chosen and provided as an input to CGT-PLAN. This is done by identifying the areas around nodes in the Iowa system topology that overlap with the green colored zones shown in Figure 2.9, which signify both adequate wind speed and sufficient feasible area to build wind farms. These nodes are then assigned as wind generation expansion candidates for the co-optimized planning software to consider.

CHAPTER 3. CO-OPTIMIZED GENERATION AND TRANSMISSION EXPANSION PLANNING FOR THE IOWA POWER SYSTEM

3.1. Overview of Co-optimization

Optimization models have always been a part of energy system planning, in the sense that it is the most important tool which helps planners to explore planning trajectories and to take decisions on energy infrastructure investments. The traditional approach to capacity expansion planning has been to plan generation resources first, followed by planning transmission resources (Figure 3.1). Co-optimization assesses both generation and transmission together in order to identify the optimal least cost combination that may not have been encountered in the traditional approach [16].

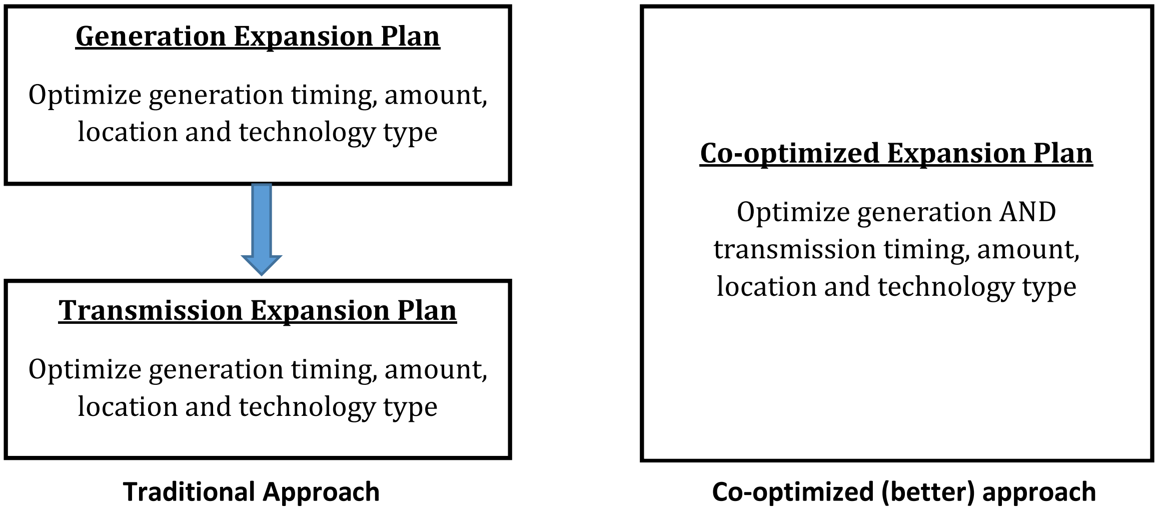


Figure 3.1 Traditional planning vs. Co-optimized planning approach

Co-optimization is the simultaneous identification of two or more related classes of investment decisions within one optimization strategy [15]. In this project, these ‘classes of investment’ include decisions to build generation and transmission. Since the decision to build generation at a certain location certainly affects the decision to build or expand transmission at that location in a particular time period, a co-optimization of these two related decisions must be as good as, or better than if they were sequentially optimized, because co-optimization identifies less costly solutions while satisfying all generation and transmission expansion planning constraints simultaneously. This is particularly advantageous when co-optimization is used in a vertically integrated utility to identify lower-cost combined generation and transmission expansion plans, rather than using the traditional planning approach.

In the context of a disaggregated market environment where generation and transmission are developed by separate organizations, co-optimization has been referred to as ‘transmission planning accounting for market response’ or ‘anticipative planning’, so named because it identifies transmission investment in anticipation of where attractive generation investment will take place [15].

Co-optimized planning can be thought of as a tradeoff between investing in generation and transmission infrastructure based on certain criteria. Sometimes, building cheaper generation farther away from the load plus the transmission required to transfer the energy is economically more viable than building expensive generation closer to the load, as shown in Figure 3.2. In other situations, investments in transmission infrastructure does not necessitate investment in new generation, and it helps that transmission infrastructure, being a lot cheaper to build compared to generation, offers much greater value in terms of cost savings. Co-optimization identifies the most optimal, albeit least cost solution in such a scenario.

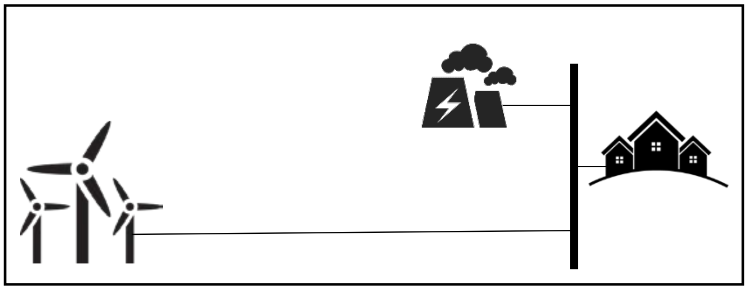


Figure 3.2 An illustration of co-optimization options

ISU’s Co-optimized Generation and Transmission Expansion Planning (CGT-PLAN) software has been formulated and coded by current and previous researchers in Dr.McCalley’s research group. It identifies multi-year generation and transmission investment decisions to satisfy demand and reserve requirements while minimizing net present value of long-term investment plus operational costs. These decisions are provided in terms of technology, capacity, location and timing.

A simple representation of the CGT-PLAN formulation is as follows:

Minimize: *Net Present Value {Gen. and Tr. Investment costs + Fixed O&M costs + Variable O&M costs + Fuel costs + Environmental costs}*

Subject to: *Operational generation and transmission constraints*

3.1.1. The ‘hybrid’ model

A generation expansion planning problem is usually written as a linear program (LP), whereas a transmission expansion planning problem using “DC” (or linearized) power flow equations is formulated as a mixed integer nonlinear program (MINLP), but the so-called “disjunctive” representation of the power flow equations affected by transmission candidates transforms the problem to a mixed integer linear program (MILP). The transmission expansion problem can also be formulated as a ‘transportation’ model (also called a ‘pipes and bubbles’ model) in which the effect of impedance of the transmission lines is neglected. This makes the problem an LP, but the model experiences a significant loss in fidelity.

To alleviate this problem, a ‘hybrid’ transmission model is used here which utilizes the DC power flow representation for existing circuits and the transportation model for candidate circuits [18]. Doing so preserves the fidelity of the original system topology, simultaneously reducing computational burden and time by making the formulation an LP, thus avoiding the MILP formulation. The co-optimized planning formulation using hybrid model for transmission is described in section 3.4.

3.2. Existing Iowa Power System Topology

A dataset representing the Iowa power system was used; it consists of 204 buses and 298 circuits. It was developed using only public data [3][13][28][29]. The system topology used in this work is illustrated in Figure 3.3.

Locations, names and voltage levels of buses and circuits were identified using the public data previously cited, and every effort was made to ensure a reasonable representation of Iowa’s power system topology. Only those circuits with a voltage rating of 115kV and above have been considered in the topology and for expansion.

The power grid infrastructure located in states bordering Iowa is modeled in a very simple manner as a set of five nodes, where each node represents a positive or negative power injection to represent the export out of Iowa or import into Iowa, respectively. These nodes are connected to Iowa by fictitious transmission lines which represent an aggregation of several lines actually present in the external power systems. It is assumed that large wind investment is also made in areas north and west of Iowa. Thus, with load centers being south and east of Iowa, power flows from the north and west to the south and east are indicated by the large red arrows in Figure 3.3.

All existing generation and retrofits as of December 2015 have been taken into account using information from the U.S. Energy Information Administration's state profile for Iowa (using their interactive online map) [3]. News articles and reports by utilities and environmental organizations on planned generation, retirements and retrofits were also utilized in some cases [5][30].

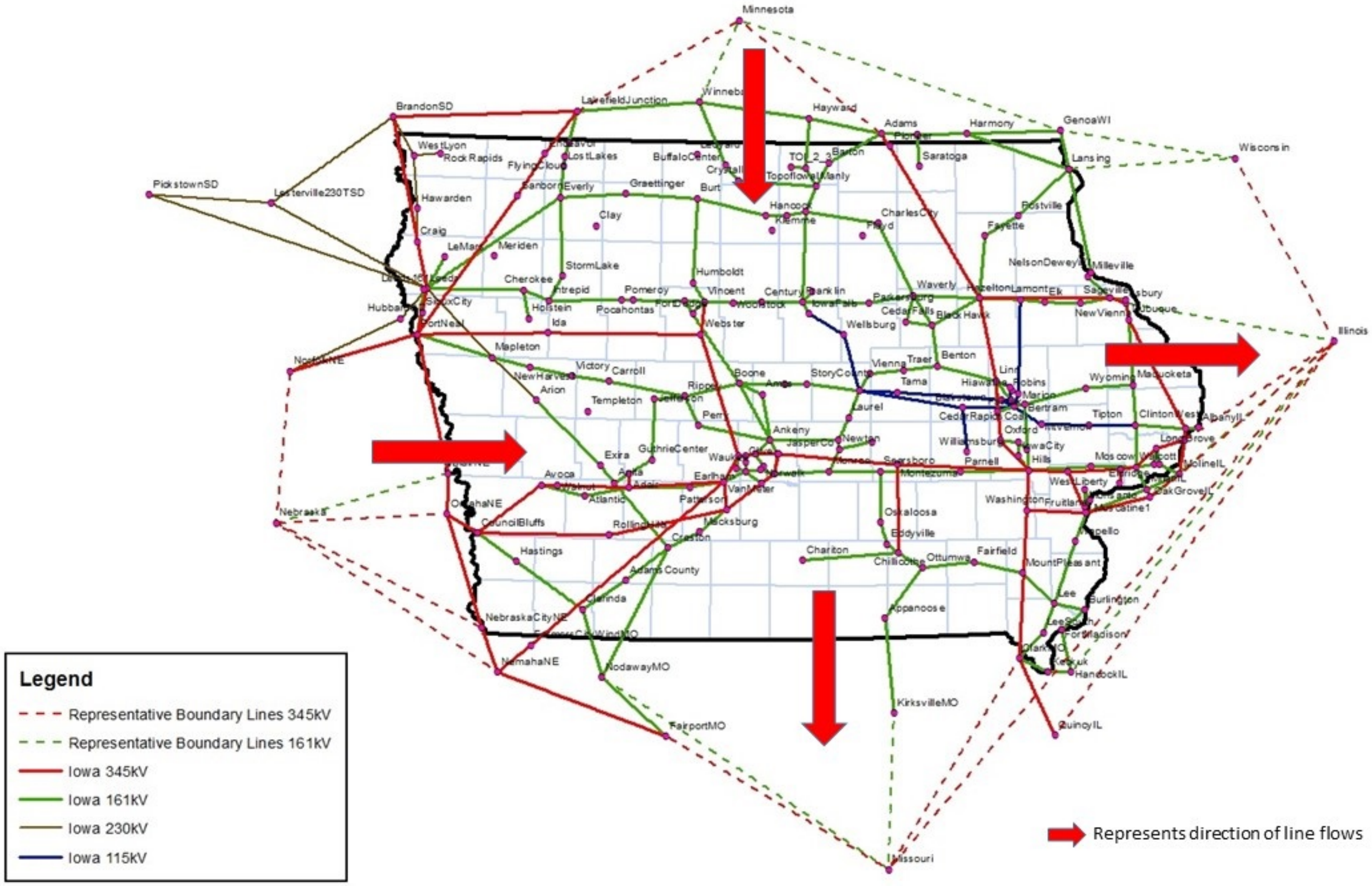


Figure 3.3 Iowa power system topology (>=115kV) connected to fictitious external nodes

3.3. Assumptions for the Planning Process

Co-optimized expansion planning is performed for a planning horizon of 20 years (2016-2036) and a very high wind penetration future in which at least 20 GW installed wind generation capacity is present in Iowa.

Under a high-wind future, it is expected that flows in the fictitious transmission lines external to Iowa will generally trend southward and eastward, away from potentially high wind resources in Minnesota, South Dakota and Nebraska, towards the large load centers in Missouri and Illinois. Since these fictitious lines represent an aggregation of the power systems external to Iowa, the capacity of these lines have been assigned very large values compared to the capacity of lines inside Iowa. Additionally, the injections from the external buses representing the five neighboring states have been increased at 1% every year to simulate the increase in generation and demand in these states.

Along with new generation candidates, existing generation is also allowed to expand. However, only wind generation, combustion turbine gas plants and combined cycle gas plants are allowed to expand, considering the shift towards renewable sources of energy and the slow phasing-out of coal. Solar is not being considered in this study because of its low penetration in Iowa, with only 34 MW of installed capacity by the end of 2015 [31]; information in 2016 suggests that this assumption may be revised for future studies. A reserve requirement of 15% above peak demand is also enforced.

Data for generation costs (fixed and variable O&M costs, fuel costs, capital costs for building new generation) and heat rate data were obtained from the U.S. Energy Information Administration [32][33][34][35][36].

Demand data per bus, though not explicitly available, was calculated using the method described in [13] by distributing the total summer peak load (obtained from the operational data sheet of form EIA-861) proportional to the population around each bus [37]. A uniform 1% load growth was assumed based on estimates by the Eastern Interconnection Planning Council [38]. The peak demand at each bus was assumed to be 5% above the maximum value of demand calculated at each bus.

Three load blocks were used to simulate peak, semi-peak and off-peak conditions based on regular use patterns, as shown in Table 3.1.

Table 3.1 Load blocks

Load block	Peak condition	Duration (hours)
p1	Peak	2190
p2	Partial peak	4380
p3	Off-peak	2190

Capacity factors for wind generation were calculated at each bus having existing or candidate wind generation using actual energy production data for 2014 and 2015 from the EIA-923 Annual Electric Utility Data form [39]. For candidate generation sites where the capacity factor could not be calculated due to lack of existing wind generation at the bus, it was estimated by observing the general trend around the particular bus.

Considering the need to promote renewable energy and the possibility of a tax on carbon being imposed to discourage the use of polluting conventional generation, a carbon tax beginning at \$15/TCO_2 in 2017, \$25/TCO_2 in 2018, and then increasing at a rate of 3.5% per annum plus inflation until it hits \$100/TCO_2 in 2016 dollars has been imposed on the model. This is the same carbon tax rate as proposed by the state of Washington [40].

Taking a cue from typical sizes for wind and gas installations, generation of each technology type at each bus is allowed to expand to a maximum of 2000 MW of installed capacity. The discount factors are computed using a discount rate fixed at 5%. Appendix A provides more information on characterization of the Iowa power system.

3.4. Co-optimized Planning Formulation

CGT-PLAN has been adapted according to requirements for the Iowa power system by appropriately modifying the constraints to suit modeling and expansion planning requirements.

The CEP is formulated as follows, in GAMS:

Minimize:

$$
\begin{aligned}
\mathrm{Obj} = & \sum_{i,t,s} (\zeta_t \cdot (\mathrm{VoLL} \cdot \mathrm{LNS}_{i,t,s} \cdot \mathrm{h}_s)) \\
& + \sum_{Lc,i,j,t} (\zeta^{\mathrm{V}}{}_t \cdot \mathrm{LExpCost}_{Lc,i,j} \cdot 1000 \cdot \mathrm{LCap}^{\mathrm{Add}}{}_{Lc,i,j,t}) \\
& + \sum_{Gi,i,Gt,t} (\zeta^{\mathrm{V}}{}_t \cdot \mathrm{GExpCost}_{Gi,i,Gt,t} \cdot 1000 \cdot \mathrm{GCap}^{\mathrm{Add}}{}_{Gi,i,Gt,t}) \\
& + \sum_{Gi,i,Gt,t} (\zeta_t \cdot \mathrm{FOM}_{Gi,i,Gt} \cdot 1000 \cdot \mathrm{GCap}^{\mathrm{Tot}}{}_{Gi,i,Gt,t}) \\
& + \sum_{Gi,i,Gt,t,s} (\zeta_t \cdot \mathrm{VOM}_{Gi,i,Gt} \cdot \mathrm{h}_s \cdot \mathrm{Pg}_{Gi,i,Gt,t,s}) \\
& + \sum_{Gi,i,Gt,t,s,F} (\frac{\zeta_t \cdot \mathrm{FC}_{Gt,F,t,i} \cdot \mathrm{H}^{\mathrm{g}}{}_{Gi,i,Gt,t}}{1000} \cdot \mathrm{h}_s \cdot \mathrm{Pg}_{Gi,i,Gt,t,s}) \\
& + \sum_{Gi,i,Gt,t,s,F} (\frac{\zeta_t \cdot \mathrm{CTax}_t \cdot \mathrm{CO}_{2Gt,F} \cdot \mathrm{H}^{\mathrm{g}}{}_{Gi,i,Gt,t}}{1000} \cdot \mathrm{h}_s \cdot \mathrm{Pg}_{Gi,i,Gt,t,s})
\end{aligned}
$$

Subject to:

Power Balance:

$$-\sum_{Li,i,j}(\mathrm{Pf}_{Li,i,j,t,s})+\sum_{Li,j,i}(\mathrm{Pf}_{Li,j,i,t,s})+\sum_{Gi,Gt}(\mathrm{Pg}_{Gi,i,Gt,t,s})=\mathrm{d}_{i,t,s}-\mathrm{LNS}_{i,t,s}$$

$\forall i,t,s$

Generation Capacity:

$$\mathrm{GCap}^{\mathrm{Tot}}{}_{Gi,i,Gt,t}=\mathrm{GCap1}_{Gi,i,Gt}+\sum_{t1|(\mathrm{ord}(t1)\le\mathrm{ord}(t))}(\mathrm{GCap}^{\mathrm{Add}}{}_{Gi,i,Gt,t1}-\mathrm{GCap}^{\mathrm{Ret}}{}_{Gi,i,Gt,t1})$$

$\forall Gen_{Gi,i,Gt},t \mid (Gt=\texttt{wind},\texttt{CC},\texttt{CT})$

Minimum Wind Capacity:

$$\sum_{t}(\sum_{Gi,i}(\mathrm{GCap}^{\mathrm{Add}}{}_{Gi,i,\texttt{wind},t}))\ge 20000$$

$\forall Gen_{Gi,i},t$

Generation Limits:

$$\mathrm{Pg}_{Gi,i,Gt,t,s}\le\mathrm{GCap}^{\mathrm{Tot}}{}_{Gi,i,Gt,t}$$

$\forall Gen_{Gi,i,Gt},t,s$

Wind Generation Limits:

$$\sum_{s}(\mathrm{h}_{s}\cdot\mathrm{Pg}_{Gi,i,\texttt{wind},t,s})\le\sum_{s}(\mathrm{h}_{s}\cdot\mathrm{CF}^{\mathrm{W}}{}_{i,t,s})\cdot\mathrm{GCap}^{\mathrm{Tot}}{}_{Gi,i,\texttt{wind},t}$$

$\forall Gen_{Gi,i,'wind'},t$

Hydro Generation Limits:

$$\sum_{s}(\mathrm{h}_{s}\cdot\mathrm{Pg}_{Gi,i,\texttt{hydro},t,s})\le\sum_{s}(\mathrm{h}_{s}\cdot\mathrm{CF}^{\mathrm{H}}{}_{i,t,s})\cdot\mathrm{GCap}^{\mathrm{Tot}}{}_{Gi,i,\texttt{hydro},t}$$

$\forall Gen_{Gi,i,'hydro'},t$

Reserves:

$$\sum_{Gi,i,Gt,}(\mathrm{CCr}_{Gt}\cdot\mathrm{GCap}^{\mathrm{Tot}}{}_{Gi,i,Gt,t})\ge 1.15\cdot\sum_{i}(\mathrm{d}^{\mathrm{P}}{}_{i,t})$$

$\forall t$

Existing Line Limits:

$$\mathrm{L\_data}_{Le,i,j,\mathtt{Imp}} \cdot \mathrm{Pf}_{Le,i,j,t,s} = \theta_{i,t,s} - \theta_{j,t,s}$$

$$\forall Line_{Le,i,j}, t, s$$

$$\mathrm{Pf}_{Le,i,j,t,s} \le \mathrm{L\_data}_{Le,i,j,\mathtt{Max}}$$

$$\forall Line_{Le,i,j}, t, s$$

$$\mathrm{Pf}_{Le,i,j,t,s} \ge -\mathrm{L\_data}_{Le,i,j,\mathtt{Max}}$$

$$\forall Line_{Le,i,j}, t, s$$

Candidate Transmission Limits:

$$\mathrm{LCapMax}_{Lc,i,j,t} = \mathrm{L\_data}_{Lc,i,j,\mathtt{Max}} + \mathrm{LCap}^{\mathrm{Add}}{}_{Lc,i,j,t}$$

$$\forall Line_{Lc,i,j}, t = 2016$$

$$\mathrm{LCapMax}_{Lc,i,j,t} = \mathrm{LCapMax}_{Lc,i,j,t-1} + \mathrm{LCap}^{\mathrm{Add}}{}_{Lc,i,j,t}$$

$$\forall Line_{Lc,i,j}, t$$

$$\mathrm{LCapMin}_{Lc,i,j,t} = -\mathrm{L\_data}_{Lc,i,j,\mathtt{Max}} - \mathrm{LCap}^{\mathrm{Add}}{}_{Lc,i,j,t}$$

$$\forall Line_{Lc,i,j}, t = 2016$$

$$\mathrm{LCapMin}_{Lc,i,j,t} = \mathrm{LCapMin}_{Lc,i,j,t-1} - \mathrm{LCap}^{\mathrm{Add}}{}_{Lc,i,j,t}$$

$$\forall Line_{Lc,i,j}, t$$

$$\sum_{t} (\mathrm{LCap}^{\mathrm{Add}}{}_{Lc,i,j,t}) \le \mathrm{LCLim}_{Lc,i,j}$$

$$\forall Line_{Lc,i,j}$$

$$\mathrm{Pf}_{Lc,i,j,t,s} \le \mathrm{LCapMax}_{Lc,i,j,t}$$

$$\forall Line_{Lc,i,j}, t, s$$

$$\mathrm{Pf}_{Lc,i,j,t,s} \ge \mathrm{LCapMin}_{Lc,i,j,t}$$

$$\forall Line_{Lc,i,j}, t, s$$

Maximum capacity build per bus:

$$\sum_{t} (\sum_{Gi,i,Gt} (GCap^{Add}_{Gi,i,Gt,t})) \le 2000$$

$$\forall Gen_{Gi,i,Gt}, t$$

Non-negativity:

$$\mathrm{LNS}_{i,t,s} \ge 0 \,\forall i,t,s$$

$$\mathrm{LCap}^{\mathrm{Add}}{}_{\mathrm{Li,i,j,t}} \ge 0 \,\forall \mathrm{Li,i,\,j,t}$$

$$\mathrm{GCap}^{\mathrm{Add}}{}_{\mathrm{Gi,i,Gt,t}} \ge 0 \,\forall \mathrm{Gi,i,Gt,t}$$

$$\mathrm{GCap}^{\mathrm{Tot}}{}_{\mathrm{Gi,i,Gt,t}} \ge 0 \,\forall \mathrm{Gi,i,Gt,t}$$

$$\mathrm{GCap}^{\mathrm{Ret}}{}_{\mathrm{Gi,i,Gt,t}} \ge 0 \,\forall \mathrm{Gi,i,Gt,t}$$

$$\mathrm{Pg}_{Gi,i,Gt,t,s} \ge 0 \,\forall Gi,i,Gt,t,s$$

$$\mathrm{LCapMax}_{Li,i,j,t} \ge 0 \,\forall Li,i,\,j,t$$

$$\mathrm{LCapMin}_{Li,i,j,t} \le 0 \,\forall Li,i,\,j,t$$

where:

t,t1 - Year

s - Load Block

i,j - Bus indices

Gt - Generation Technology

Gi - Generator

Gen - Set of generators by area and technology

Li - Line

Line - Set of lines and linked buses

F - Fuel Type

Le - Existing Lines

Lc - Candidate Lines

VoLL - Value of Lost Load ($/MWh)

ζ - Discount Factor with end-horizon effects

ζ^V - Discount Factor without end-horizon effects

h - Duration (hours)

d - Power Demand (MW)

d^P - Peak Power Demand (MW)

H^g - Heat Rate (Btu/KWh)

CF^H - Hydro Capacity Factor

CF^W - Wind Capacity Factor

GExpCost - Generation Expansion Cost ($/kW)

LExpCost - Transmission Expansion Cost ($/kW)

FC - Fuel Cost ($/MMBtu)

CTax - Carbon tax ($/ton)

CO_2 - Carbon Dioxide Emissions (ton/MMBtu)

CCr - Capacity Credit

GCap1 - Capacity of Existing Generation in Year 1 (MW)

LCLim - Line Investment Limit (MW)

Pf - Transmission Line Flows (MW)

θ - Bus Angle (Deg)

L_data - Matrix of Line Data

LCapAdd - Transmission Capacity Additions (MW)

LCapMax - Maximum Transmission Capacity (MW)

LCapMin - Minimum Transmission Capacity (MW)

Pg - Generation Level (MW)

LNS - Load Shedding (MW)

GCapAdd - Generation Capacity Builds (MW)

GCapRet - Generation Capacity Retirements (MW)

GCapTot - Cumulative Generation Capacity (MW)

FOM - Fixed Operation & Maintenance Cost ($/kW-yr)

VOM - Variable Operation & Maintenance Cost ($/MWh)

3.5. Results

GAMS translates the CGT-PLAN code into a .lp file. CPLEX is used to run and optimize the problem in the .lp file, and the result is written to a .sol file. A MATLAB code is then used to extract the relevant results into an excel spreadsheet to enable easier inspection and processing capabilities.

The results indicate the capacity, location, technology type and time (year) for each generation build or retirement to take place, and the capacity, time (year) and buses between which transmission investment should take place. The investment and cost results of the 20-year co-optimized generation and transmission plan for Iowa are tabulated in Table 3.2.

Table 3.2 Investment and cost results of CGT-PLAN

Cost Component	Cost (2016 $)
Generation capital cost investment	$58.82 billion
Generation fixed O&M	$22.69 billion
Generation variable O&M	$2.09 billion
Generation fuel cost	$9.11 billion
Generation carbon tax	$10.52 billion
Transmission capital cost investment	$4.82 billion
Total cost	$108.06 billion

A summary of MW capacity builds and retirements for each technology type over the planning horizon are tabulated in Table 3.3.

Table 3.3 MW capacity builds and retirements per technology type for CGT-PLAN

Generation Technology	Generation Built (MW)	Generation Retired (MW)
Wind	25319.16	0
Gas – Combustion Turbine	3258.43	1377.9
Gas – Combined Cycle	2000	1518.6
Coal	0	6112.8
Total	30577.60	9009.3

These results indicate that wind is preferred as the major source of power generation, with no wind generation being retired during the planning horizon. Almost all of Iowa's coal generation is retired within the first few years. Factors favorable to wind include imposition of a carbon tax, absence of fuel cost, low O&M costs and a good wind resource in Iowa. Though a constraint to build a minimum of 20 GW wind exists in the planning formulation, more than 25 GW wind has been indicated in the planning results.

Investment of such a large scale in wind energy requires a robust transmission infrastructure since wind generation is usually located in remote areas away from load centers. Results show that 20623 MW of transmission capacity needs to be built in order to efficiently transfer the energy produced without any load shedding.

These generation and transmission planning results are not intended to predict the future. Rather, expansion planning should be treated as an exploratory tool to observe how different scenarios will affect generation and transmission investments in the future. Additionally, capacity expansion planning does not take into account the reliability and stability of a system under each envisioned future, and such an analysis is beyond the scope of this work.

The results spreadsheet contains thousands of rows, making it difficult for a planner to process and assimilate the results in order to aid decision making. The ability to visualize these results will provide the planner with a high-level view of what the plans look like and make it much easier to communicate the plans to stakeholders. This visualization capability using ArcGIS is described in the next chapter.

CHAPTER 4. VISUALIZATION USING ARCGIS

The expansion planning results are complex and difficult to understand when directly read from the software's output. For example, the result of a single run of CGT-PLAN for the Iowa system, when extracted into a Microsoft Excel worksheet, produces more than 64,000 rows of generation builds, retirements, total builds, bus angles, transmission line expansions, line flows and load shedding data. Thus, the capability to visualize these results using GIS will have a much greater impact on how a planner understands and chooses the optimum plan, because pictures are much more effective than numerical data for communicating complex information.

4.1. Interfacing CPLEX and ArcGIS

The .sol file generated by CPLEX is processed using a MATLAB code to extract the desired results, which are then written to a Microsoft Excel spreadsheet. In order to visualize generation and transmission investments individually in ArcGIS, these results need to be sorted by technology type and converted into shape files. The approach is described in Figure 4.1.

To sort the results by technology type, a python code has been developed to extract planning results (generator name, location, capacity, year for generation builds and retirements; line name, buses, capacity, year for transmission builds) and to write them in separate .csv files. The python code also refers to another excel spreadsheet containing geographic coordinates of all the buses and links each result with the corresponding coordinates.

To create shape files from these csv files which contain spatial information for the results, iterative models were built for generation and transmission using model builder in ArcGIS. The shape files thus generated are viewed by animating them using the time slider feature in ArcGIS.

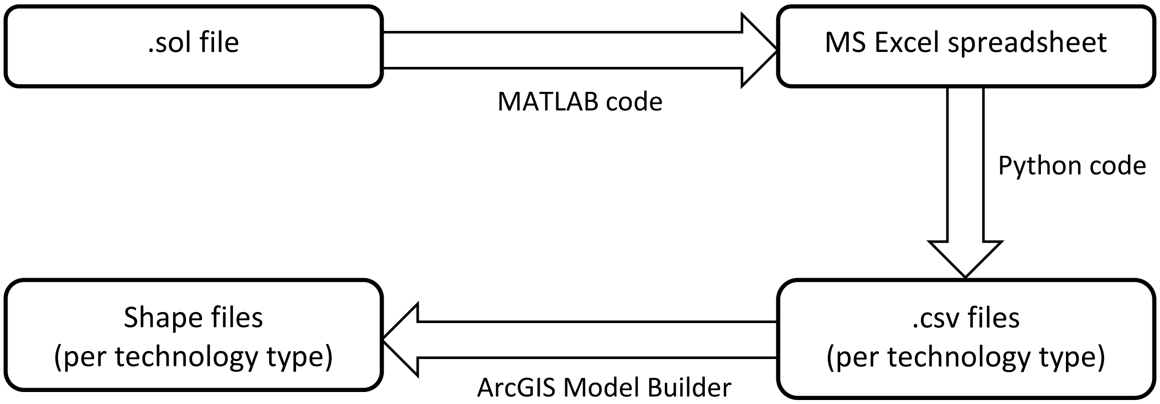


Figure 4.1 Approach to interfacing CPLEX with ArcGIS

4.2. Visualization Results

Though the total generation and transmission investment decisions can be observed by analyzing the data in the results spreadsheet, GIS visualization offers the added advantage of being able to see exactly where and how much generation or transmission is built in an interactive environment. Screenshots of every year of the planning horizon, when visualized using ArcGIS, are shown below:

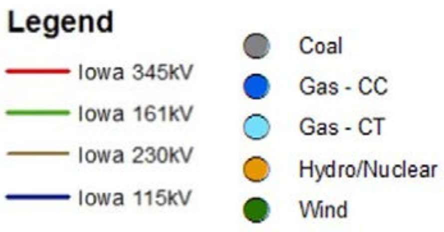


Figure 4.2 Legend for CGT-PLAN result visualization using ArcGIS

Figure 4.2 shows the legend for the visualization results. Transmission expansion build decisions for four different voltage levels in the Iowa system topology are represented using different colors, with the width of the lines proportional to the added transmission capacity. Generation builds are shown by lighter colors corresponding to those shown in Figure 4.2, retirements are shown by hollow circles and total generation capacity of each generation technology at each bus is represented by solid colors shown in Figure 4.2. Radius of the circles representing generation are proportional to the capacity built, retired or total capacity at each bus.

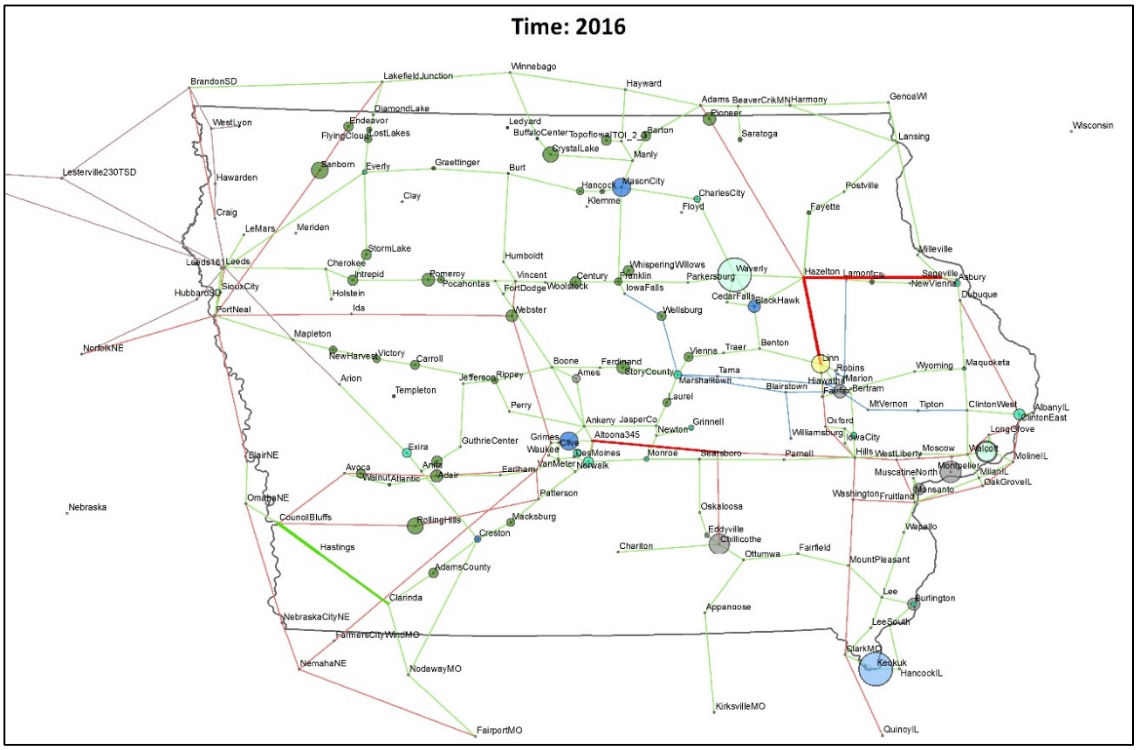


Figure 4.3 Visualization of CGT-PLAN result - Year 2016

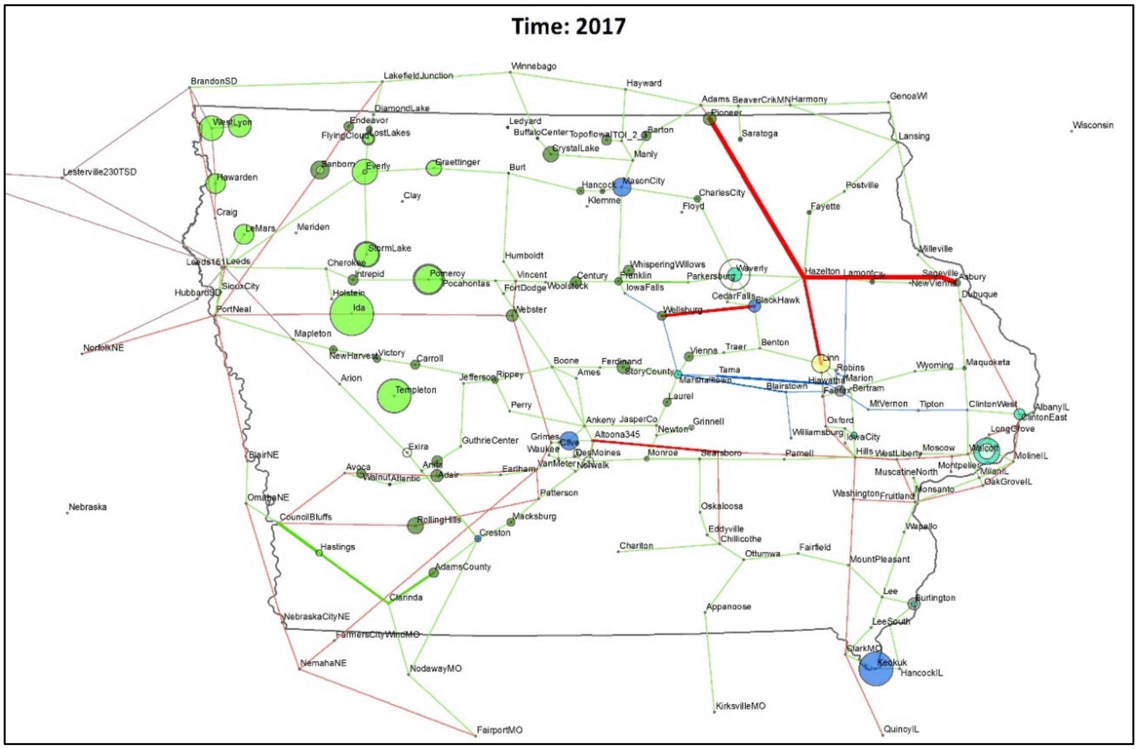


Figure 4.4 Visualization of CGT-PLAN result - Year 2017

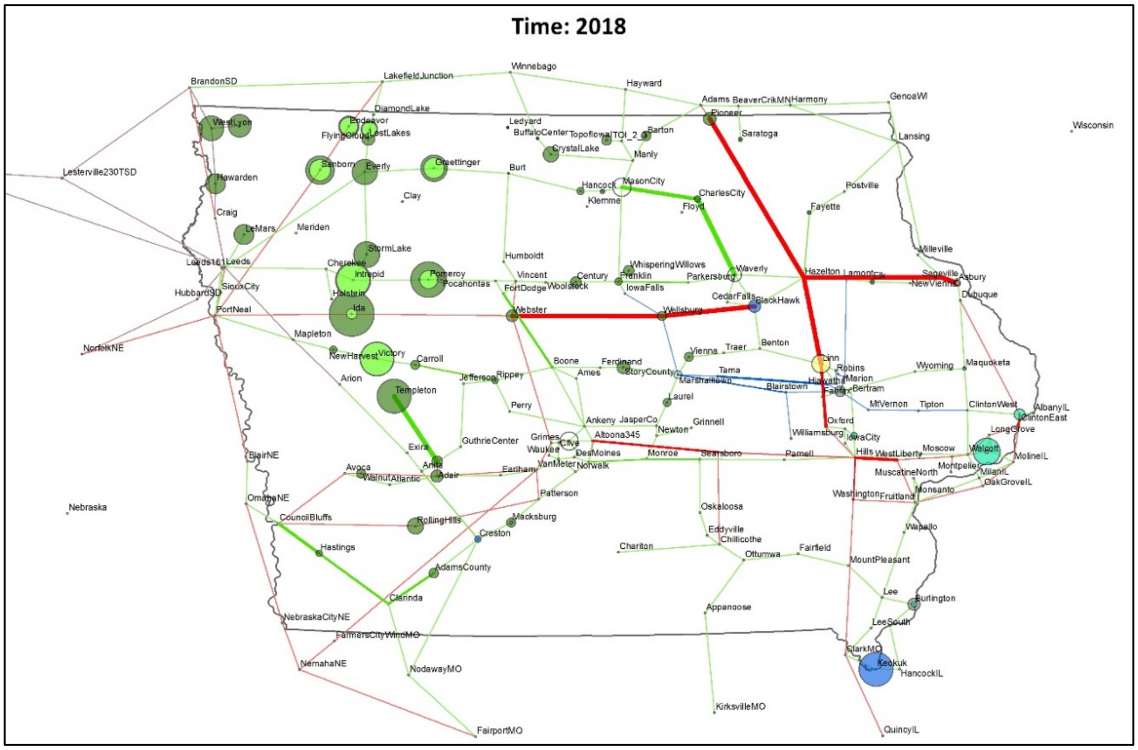


Figure 4.5 Visualization of CGT-PLAN result - Year 2018

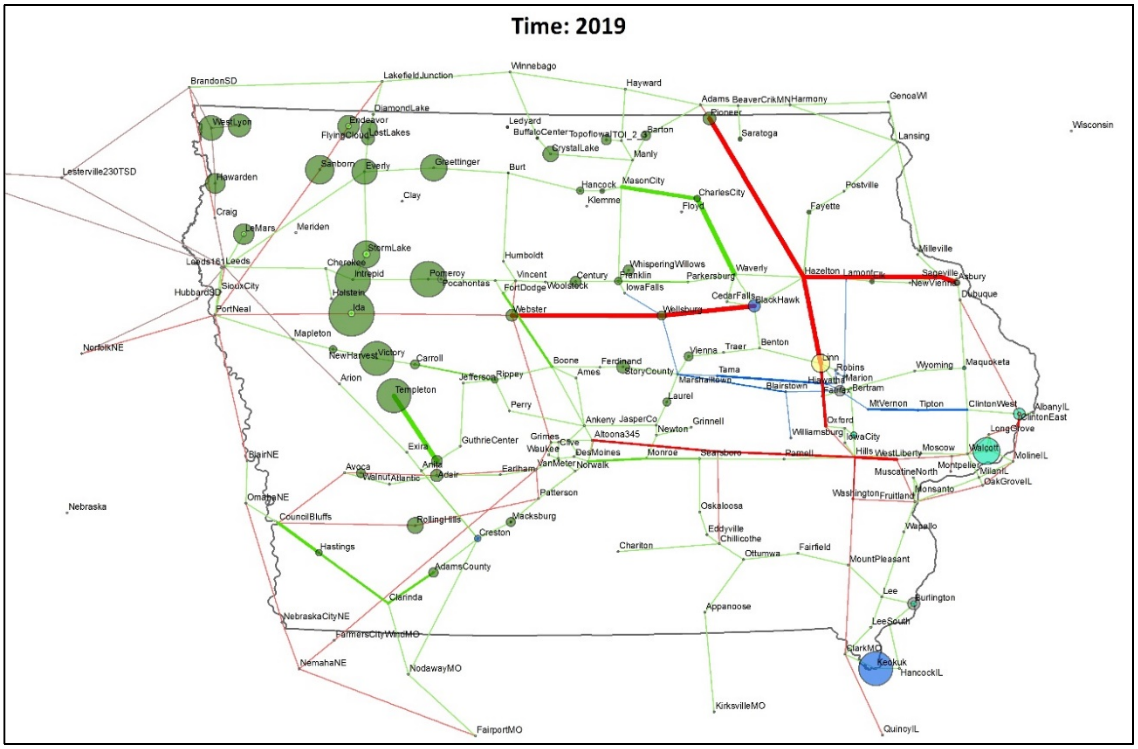


Figure 4.6 Visualization of CGT-PLAN result - Year 2019

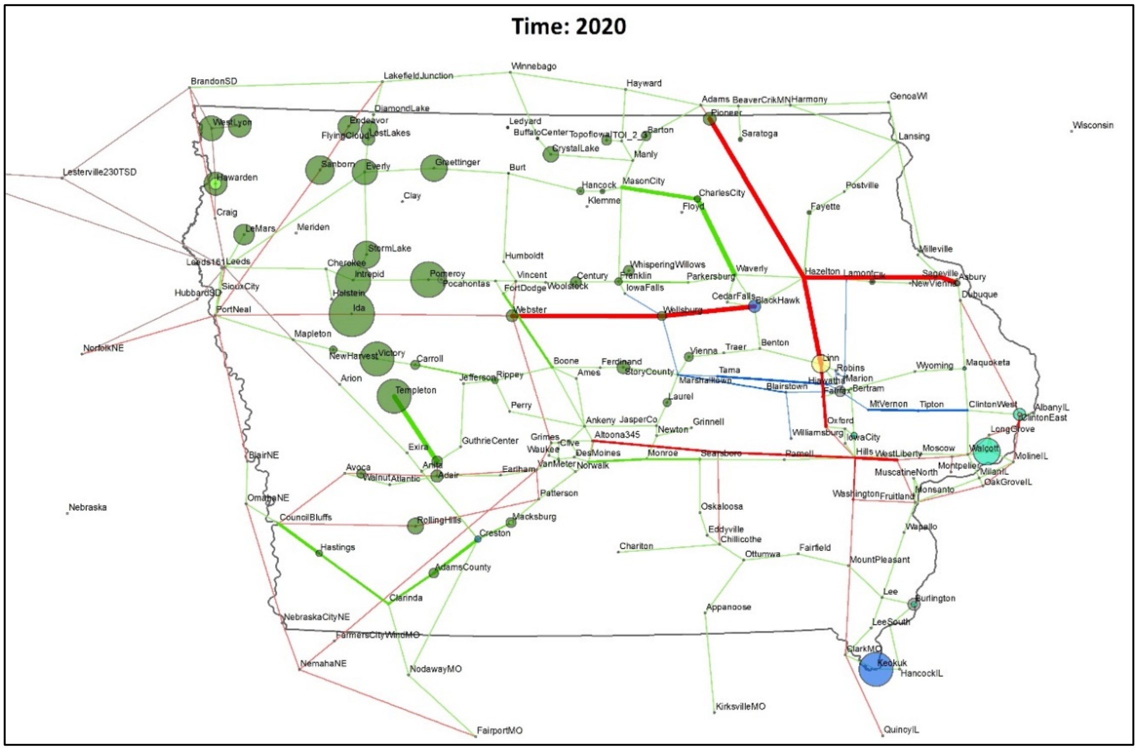


Figure 4.7 Visualization of CGT-PLAN result - Year 2020

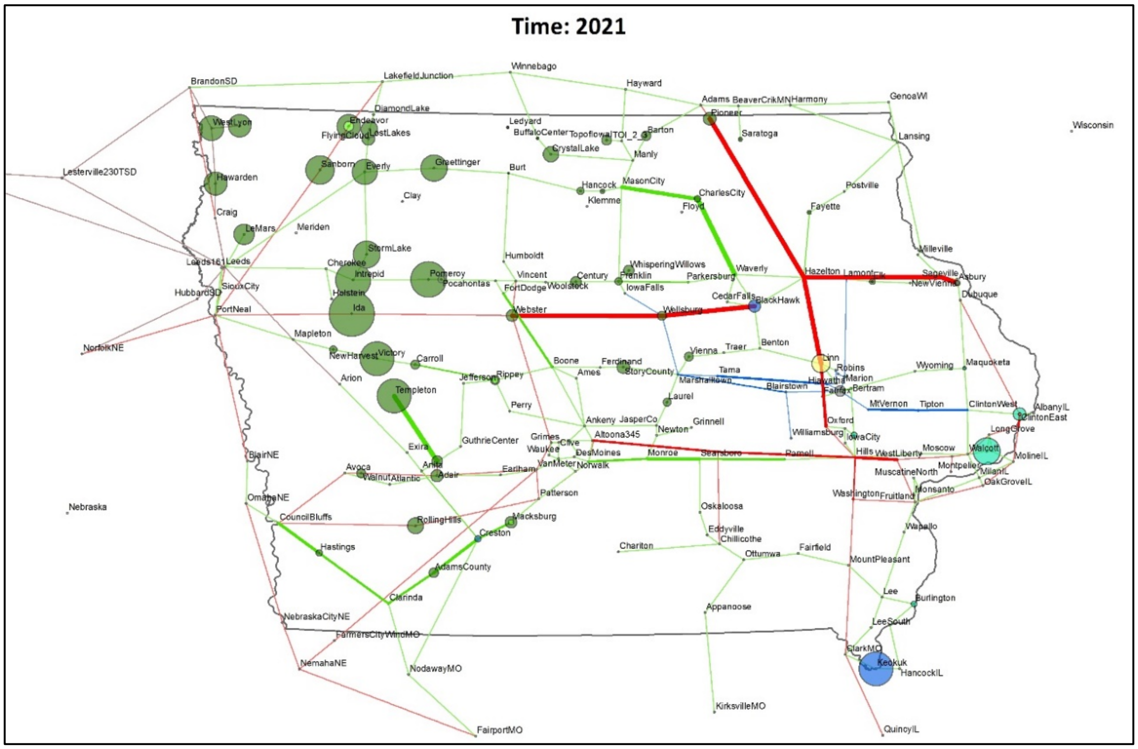


Figure 4.8 Visualization of CGT-PLAN result - Year 2021

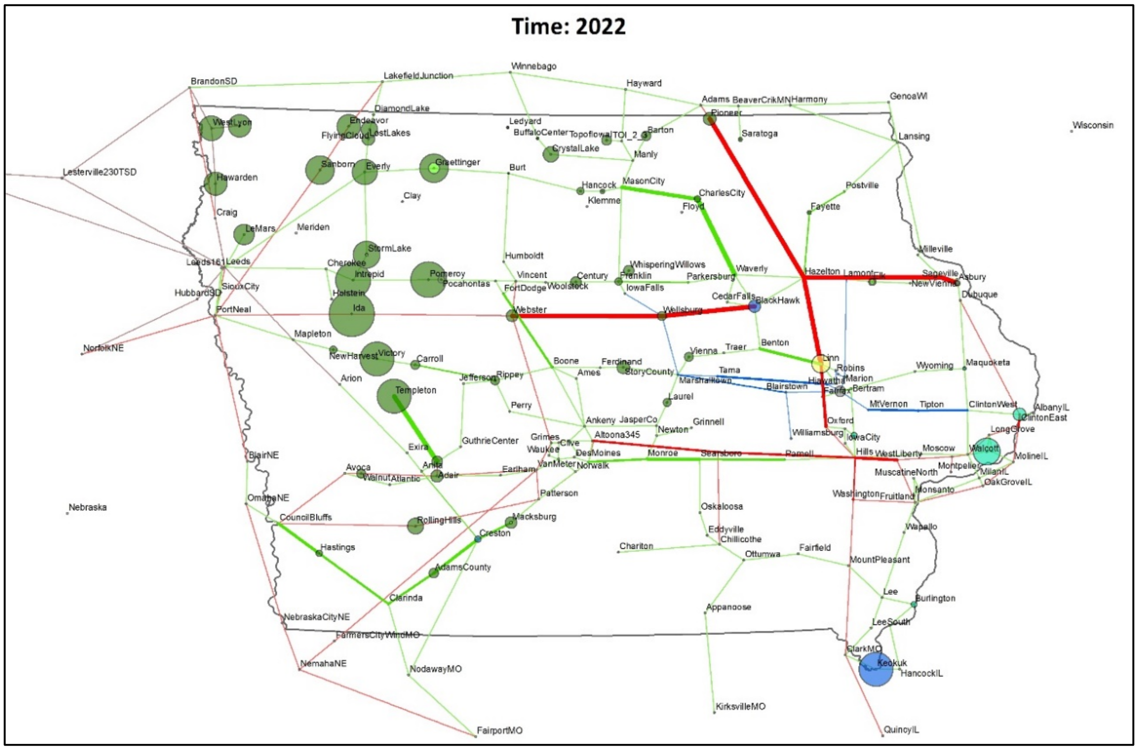


Figure 4.9 Visualization of CGT-PLAN result - Year 2022

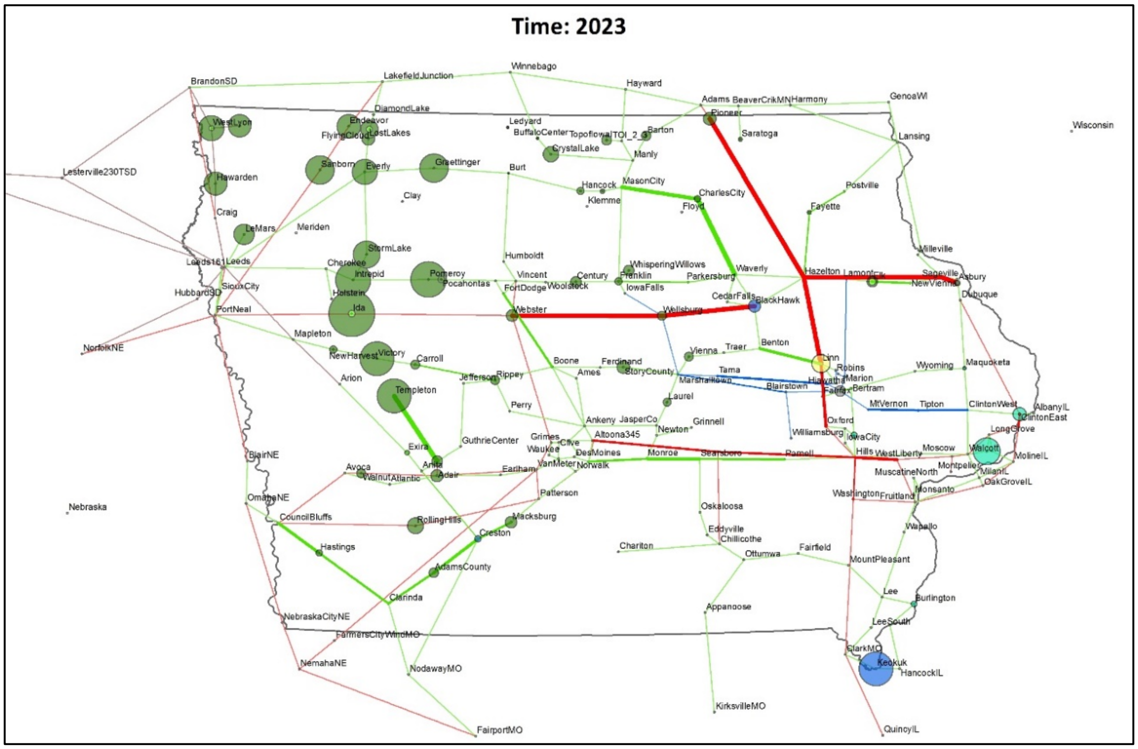


Figure 4.10 Visualization of CGT-PLAN result - Year 2023

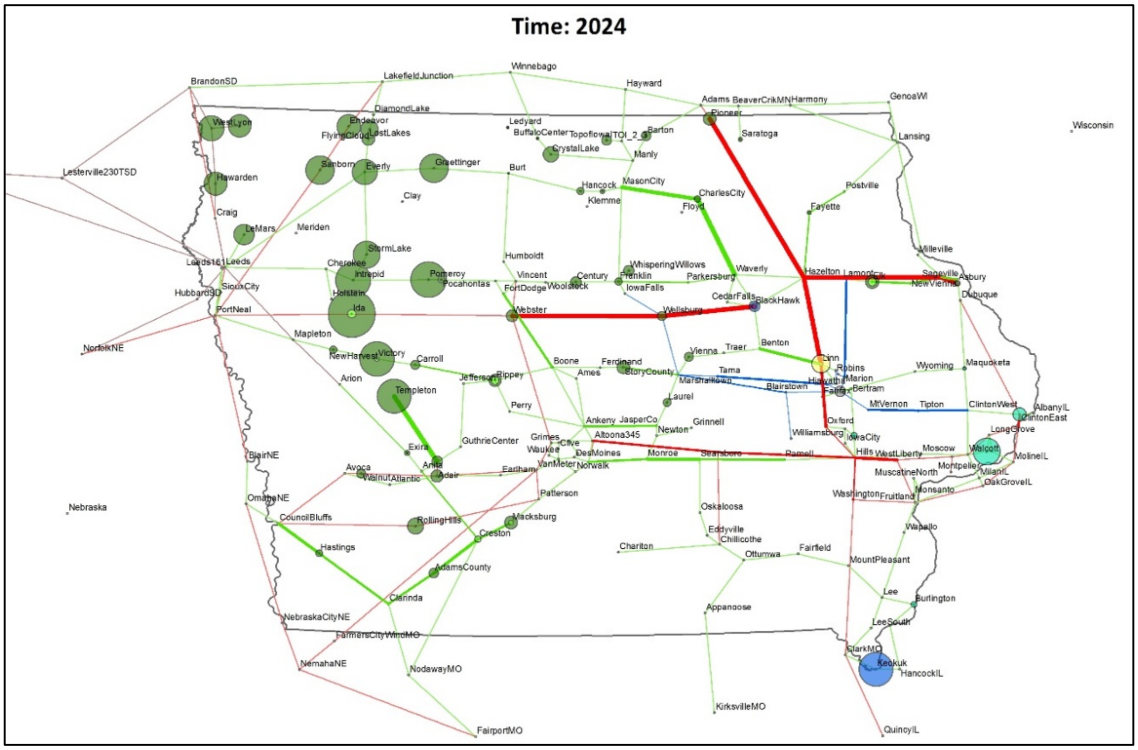


Figure 4.11 Visualization of CGT-PLAN result - Year 2024

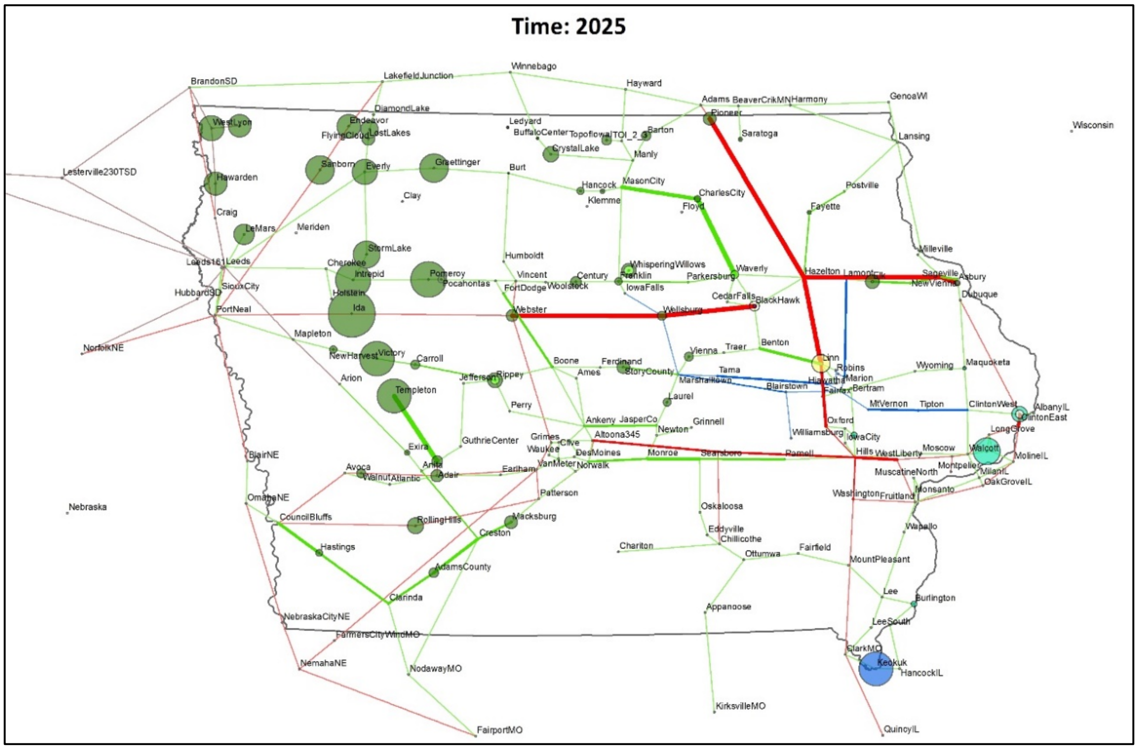


Figure 4.12 Visualization of CGT-PLAN result - Year 2025

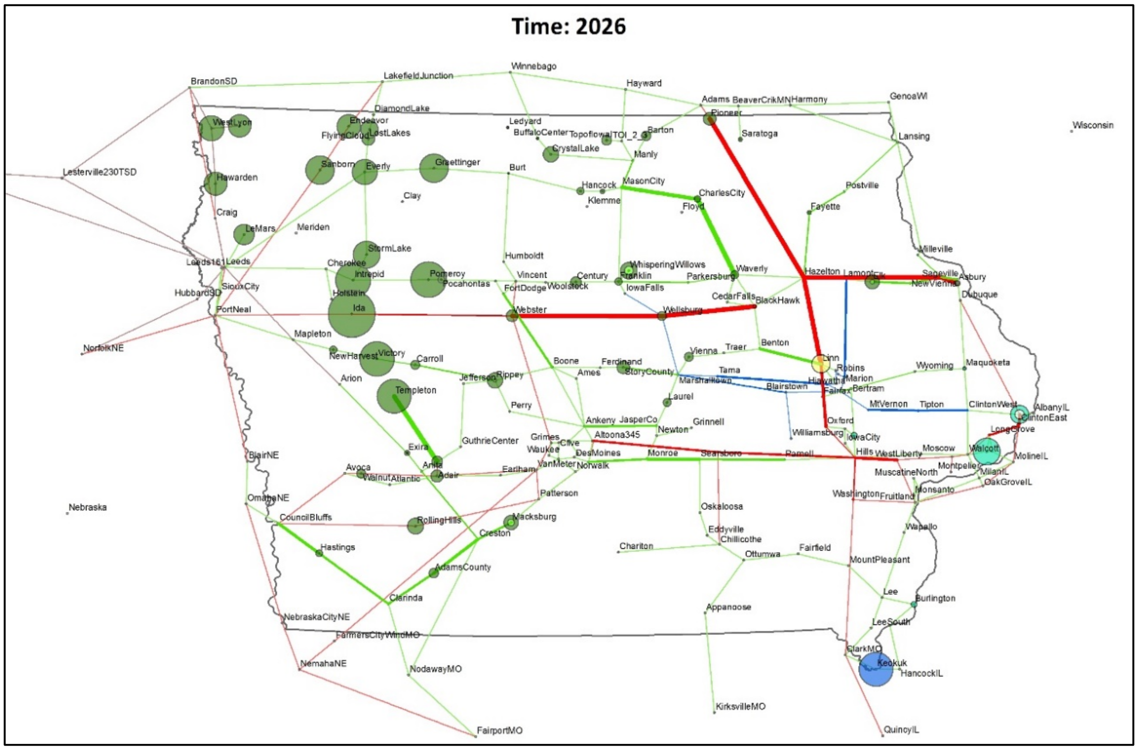


Figure 4.13 Visualization of CGT-PLAN result - Year 2026

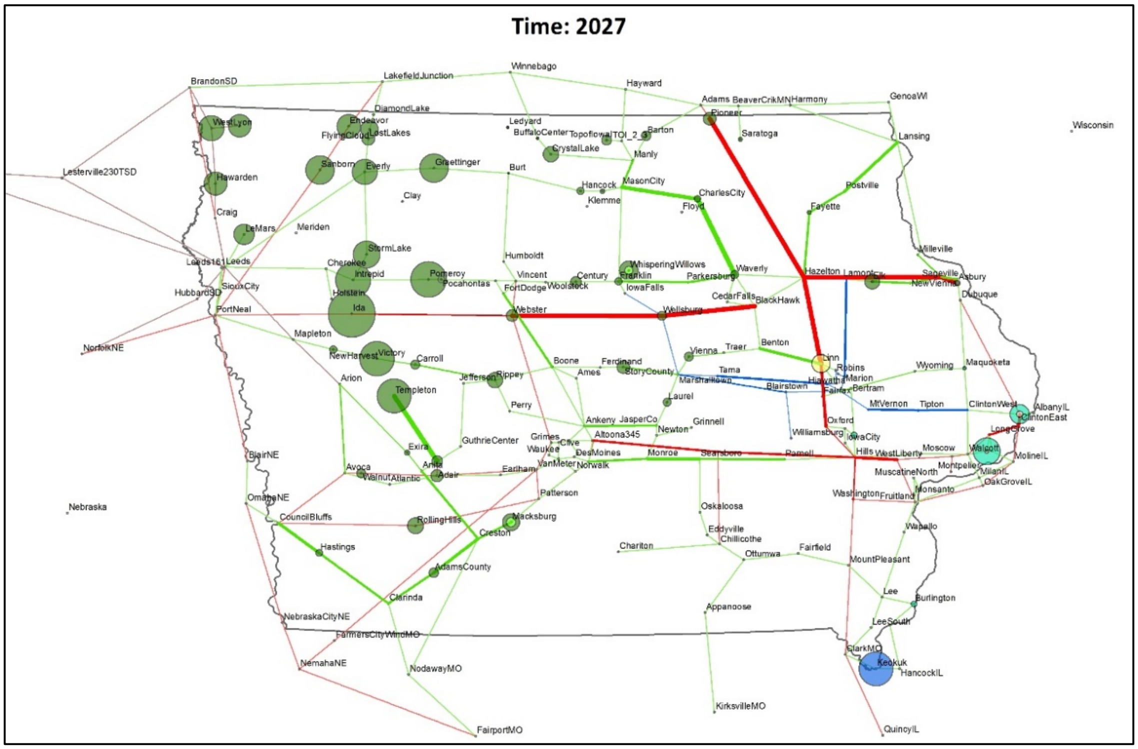


Figure 4.14 Visualization of CGT-PLAN result - Year 2027

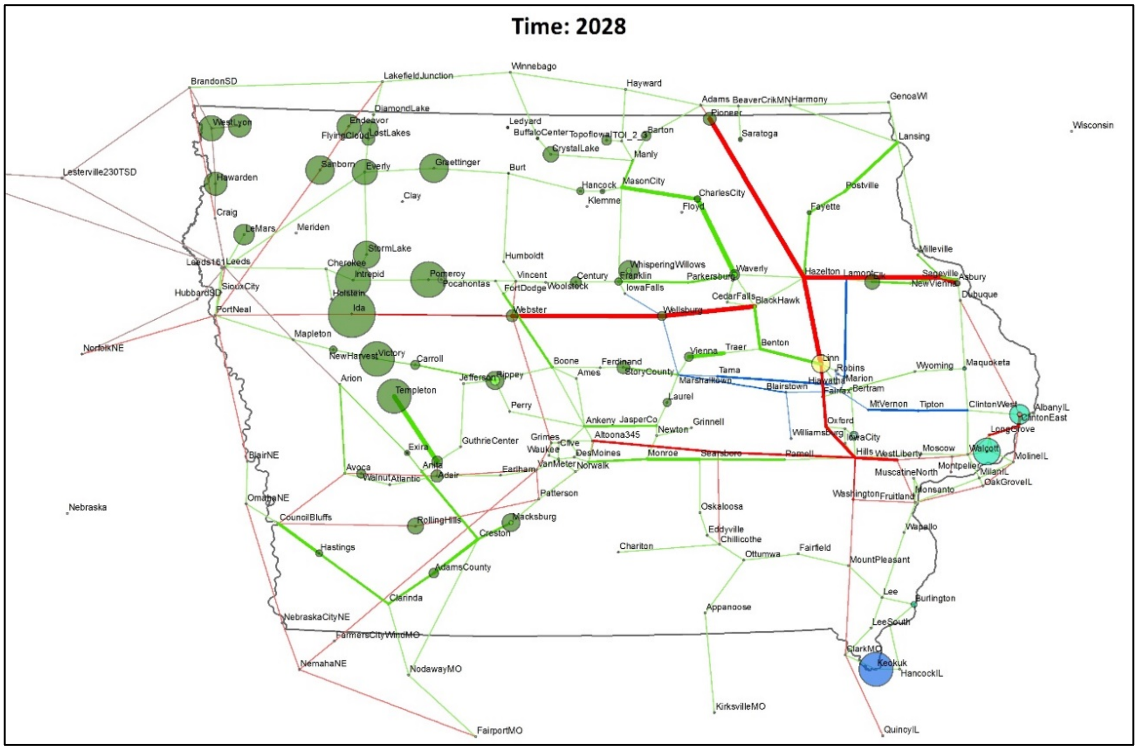


Figure 4.15 Visualization of CGT-PLAN result - Year 2028

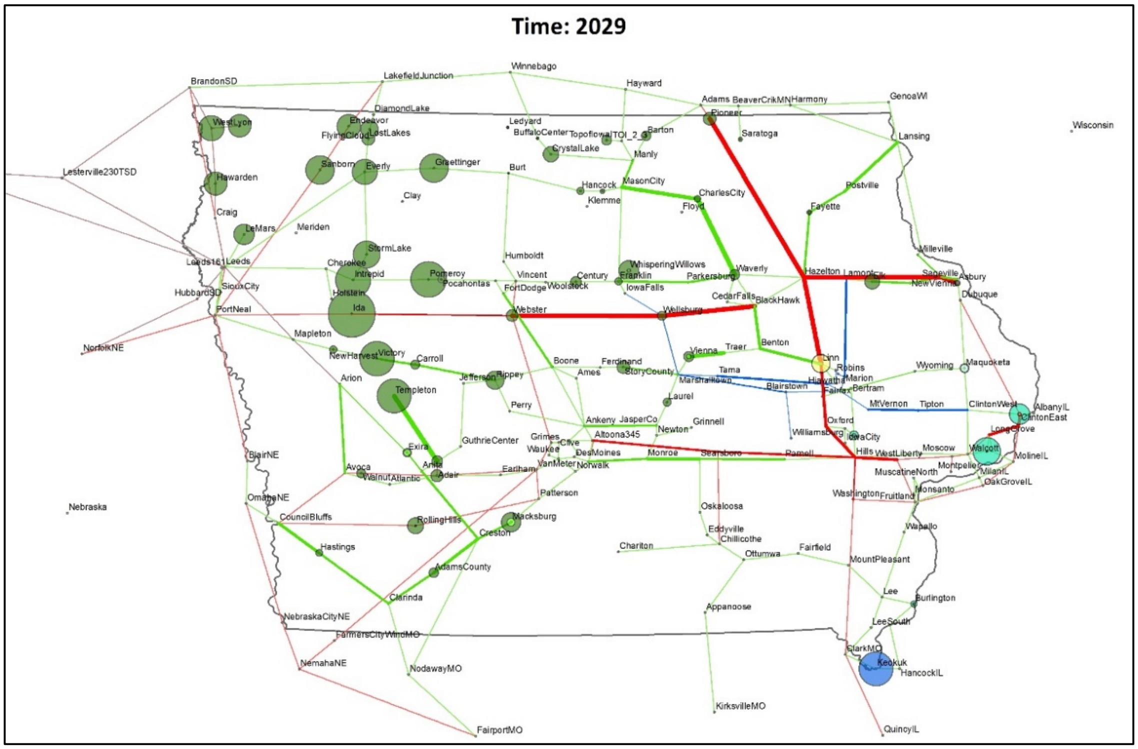


Figure 4.16 Visualization of CGT-PLAN result - Year 2029

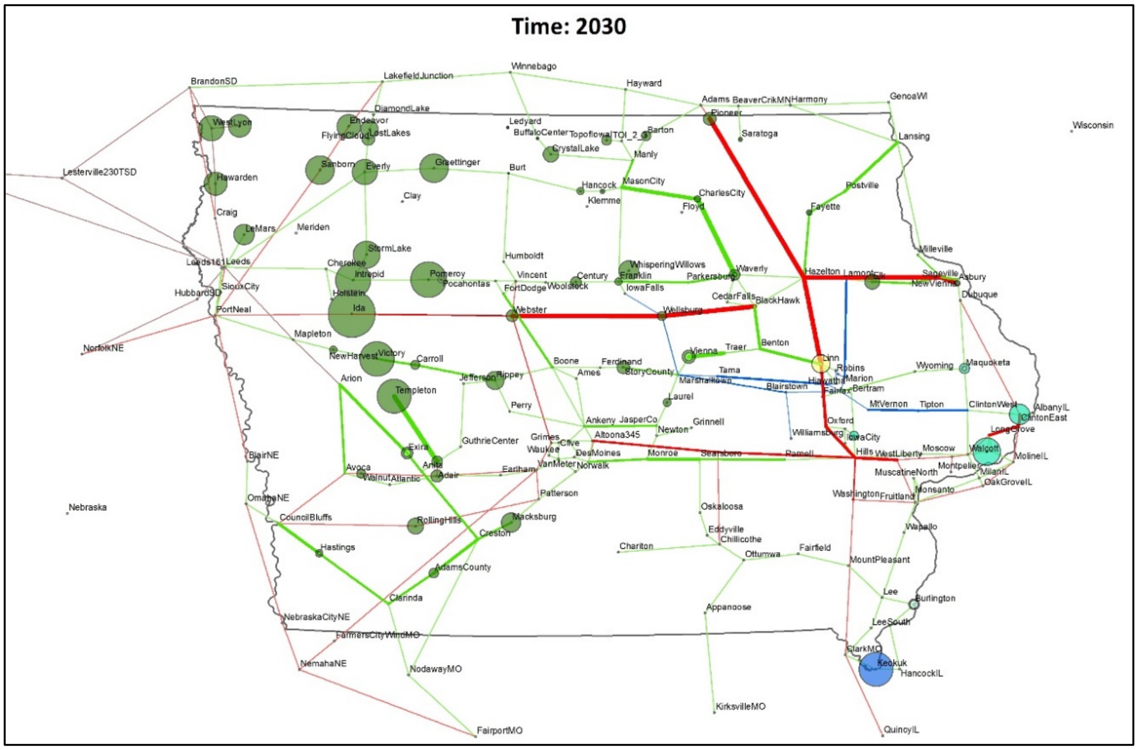


Figure 4.17 Visualization of CGT-PLAN result - Year 2030

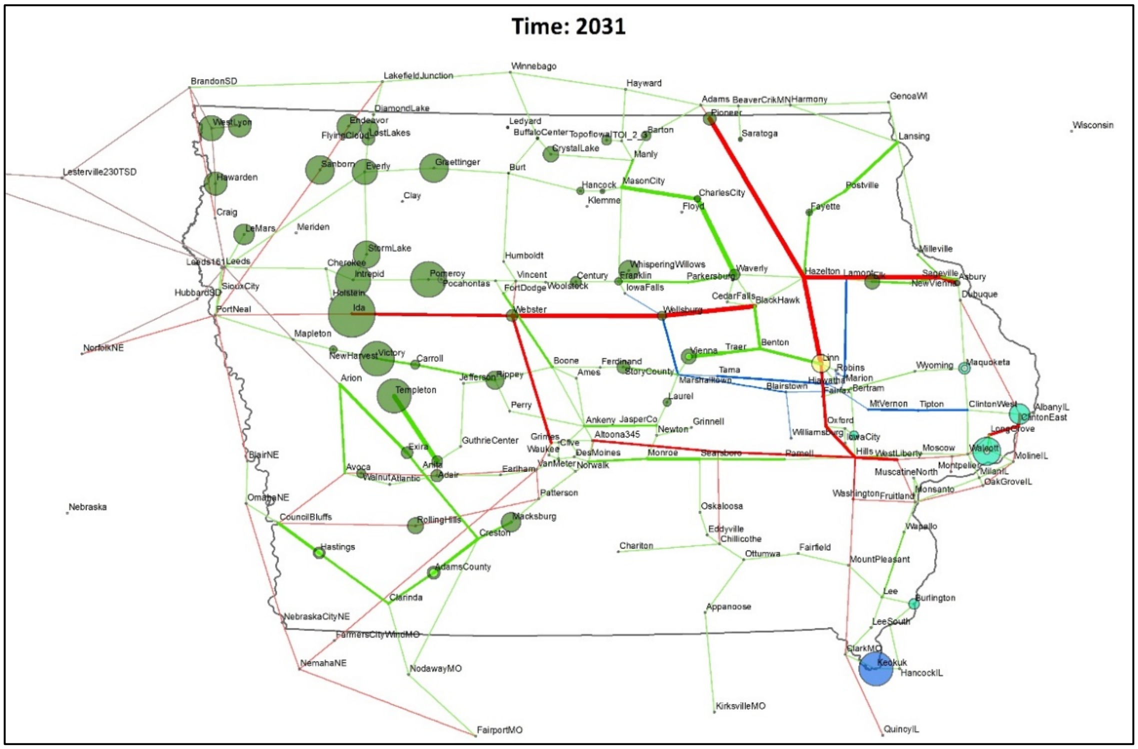


Figure 4.18 Visualization of CGT-PLAN result - Year 2031

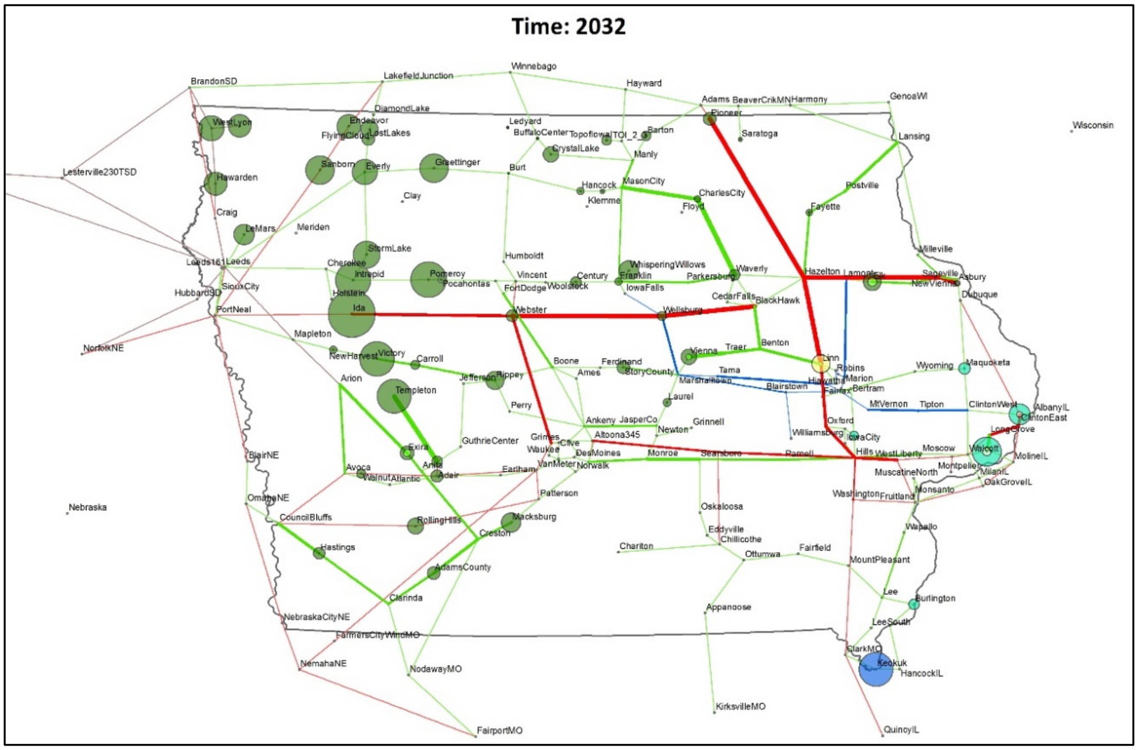


Figure 4.19 Visualization of CGT-PLAN result - Year 2032

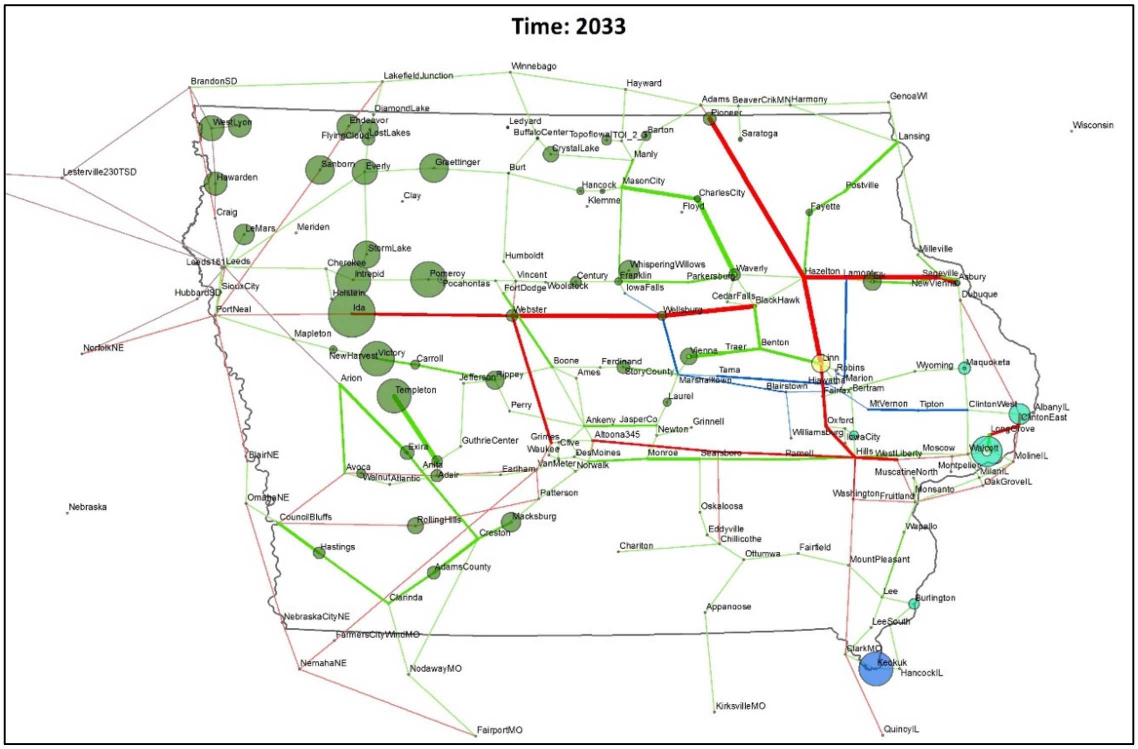


Figure 4.20 Visualization of CGT-PLAN result - Year 2033

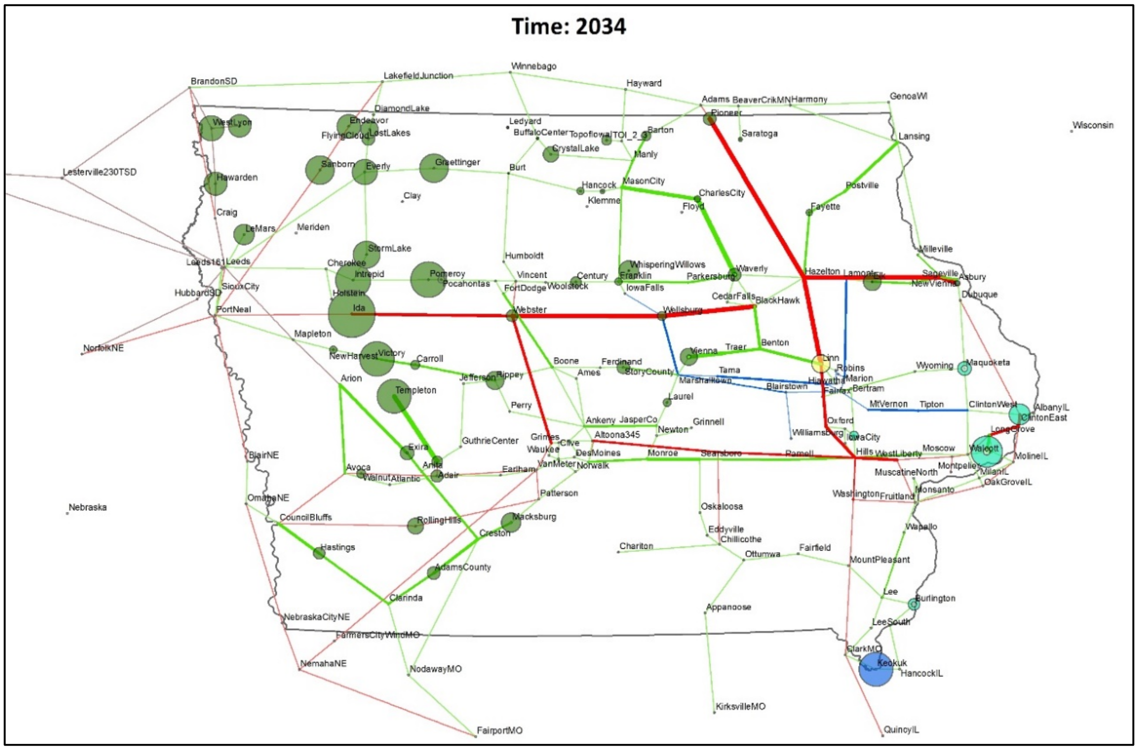


Figure 4.21 Visualization of CGT-PLAN result - Year 2034

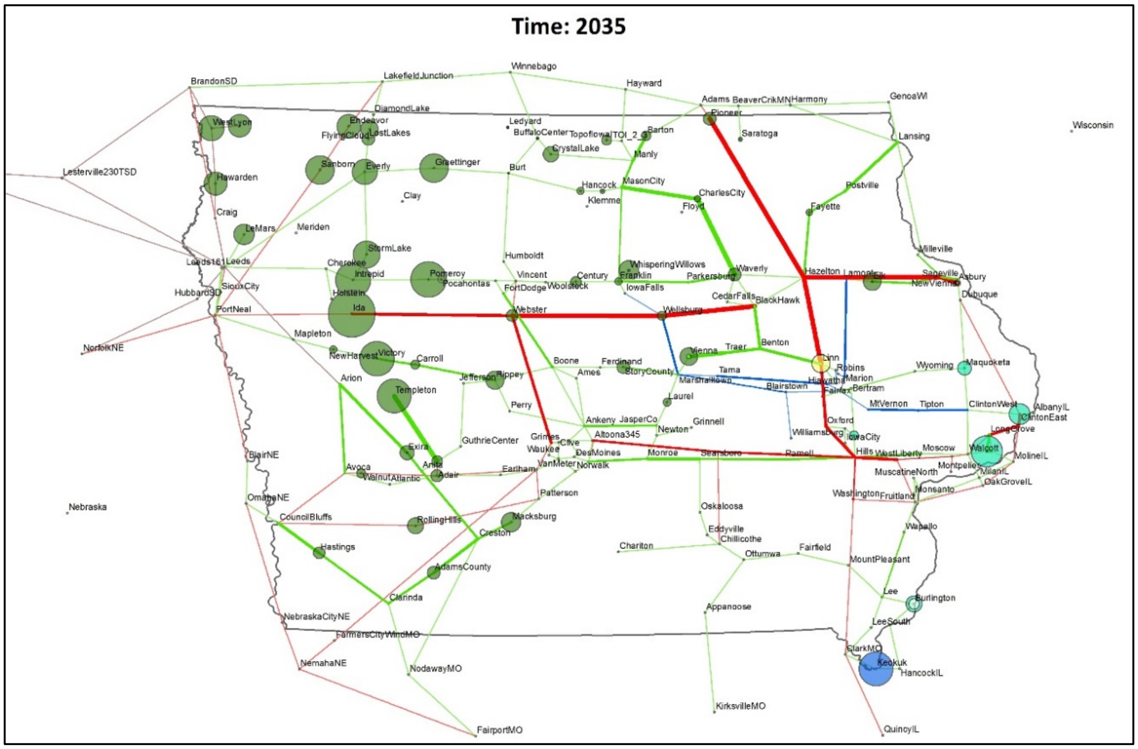


Figure 4.22 Visualization of CGT-PLAN result - Year 2035

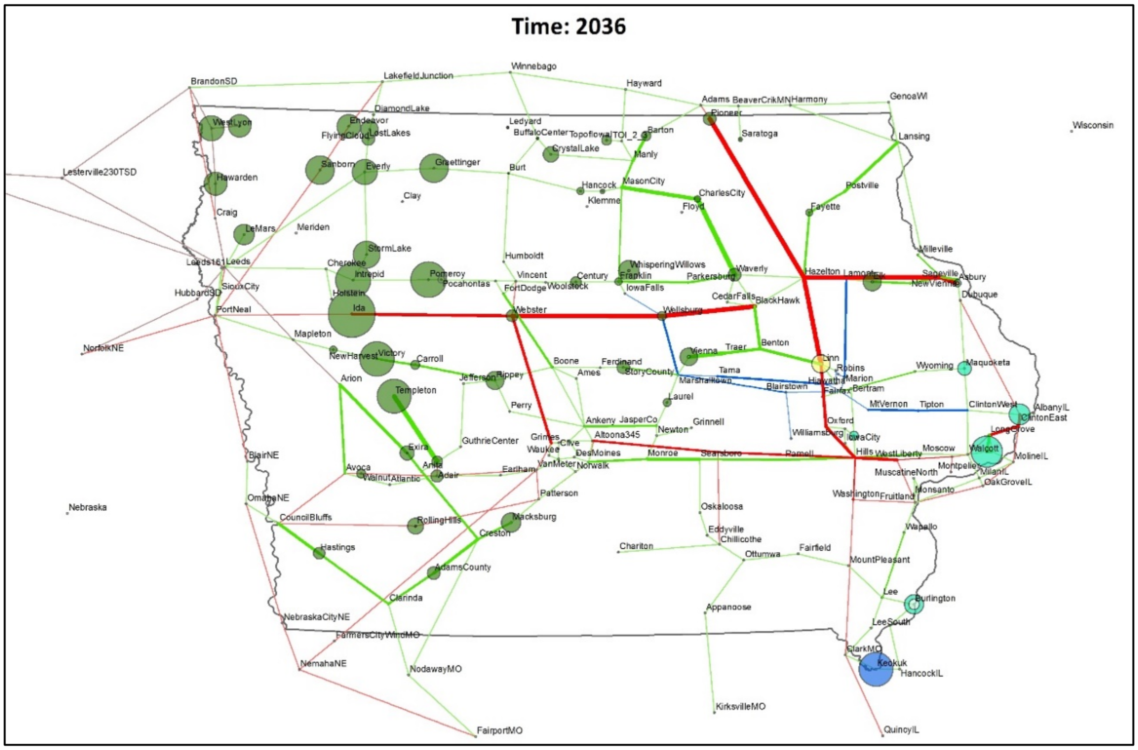


Figure 4.23 Visualization of CGT-PLAN result - Year 2036

By observing the results in ArcGIS, it is immediately evident that the majority of wind generation is built in northwestern and western Iowa where the wind resource is comparatively much better. This is in agreement with the best wind candidate sites discussed in chapter 2. A pattern to transmission expansion is also noticed – transmission infrastructure is strengthened from the generation sources towards the loads in the east and south, with some transmission being built to handle the import of wind energy from Minnesota in the north and to export it eastward into Wisconsin and Illinois.

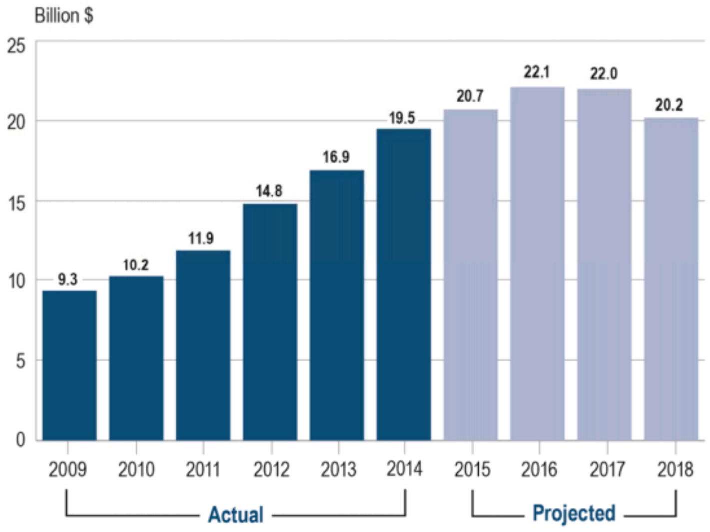
4.3. Benefits of Using GIS-based Visualization

The benefits of using GIS-based visualization for expansion planning results are listed below:

- It enables increased location accuracy.
- It allows the plan to be viewed at multiple resolutions (state, county, city, bus, etc.).
- It allows various features to be added or removed at the click of a button.
- It is dynamic since it enables data to be shared and included in other plans/studies.
- It is useful to discern patterns in the planning results, such as a pattern in the way generation is built in a region and the resulting transmission builds, or vice-versa.
- It is interactive and allows the user to choose and change how a particular feature is displayed.

CHAPTER 5. VALUE OF TRANSMISSION: A COMPARISON

In the United States, transmission investment reached a record $19.5 billion in 2014, and based on projections by the Edison Electric Institute (Figure 5.1), an additional $85 billion will be spent on transmission infrastructure through 2018 [41][42]. This motivates a discussion on the value of transmission and why expanding transmission infrastructure is important.



Note: Investment of investor-owned electric utilities and stand-alone transmission companies. Actual Investment figures were obtained from the EEI Property & Plant Capital Investment Survey supplemented with FERC Form 1 data. Projected investment figures were obtained from the EEI Transmission Capital Budget & Forecast Survey supplemented with data obtained from company 10-k reports and investor presentations. Please note that the investment totals are shown in nominal dollars and are not wholly comparable with previous versions of this chart which showed investment in Real dollars.

Source: Edison Electric Institute, Business Information Group. Updated October 2015.

Figure 5.1 Actual and projected transmission investments (2009-2018)

In this chapter, we will illustrate the value of transmission in terms of achieving clean energy goals by comparing two cases using the Iowa power system – one in which only generation expansion is allowed, and another in which generation and transmission is co-optimized.

5.1. An Example Using the Iowa Power System

The clean energy policies considered in both cases are:

- Carbon tax imposed on fossil fuel-based generation at the same rate described in section 3.3.
- Minimum 20 GW of installed wind capacity builds during the planning horizon.

Both these clean energy policies need to be met by both the cases described below, while simultaneously satisfying basic performance and adequacy requirements. The planning formulation described in section 3.4 is used for both cases, with the exception of the 'maximum capacity built per bus' constraint. This constraint is removed in order to facilitate building new generation locally to avoid load shedding in the absence of sufficient transmission capacity. All other assumptions, including demand growth, are uniform in both cases in the interest of a fair comparison.

5.1.1. Case A: Generation Expansion Only

For this case, no transmission expansion was allowed, with the resulting problem reduced to a generation expansion planning problem given the existing transmission topology and limits. The implementation of this case is estimated to cost \$124.01 billion with the minimum wind capacity constraint binding. A visual for year 2036 is shown in Figure 5.2.

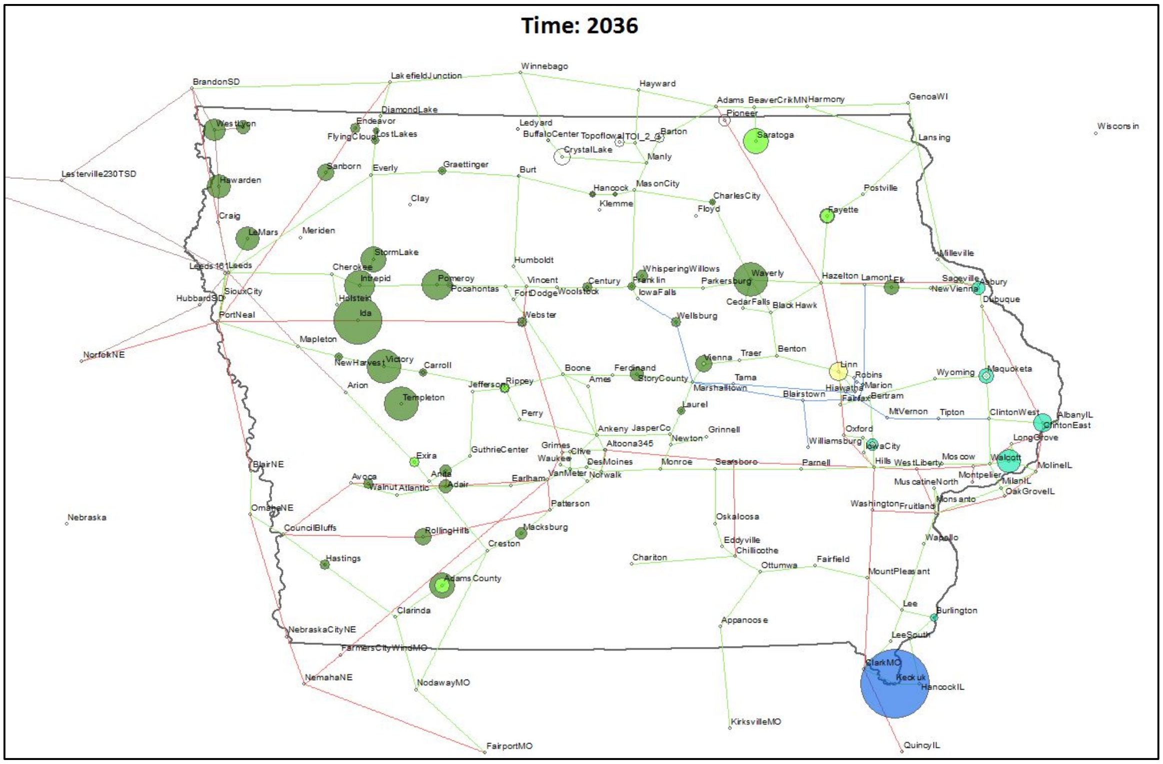


Figure 5.2 Generation Expansion Only - Year 2036

5.1.2. Case B: Co-optimized Generation and Transmission Expansion

In this case, generation and transmission investments were co-optimized similar to chapter 3 with the modification discussed earlier, leading to new results. Though all other assumptions remained the same, the removal of the constraint reduced the total cost of the objective function from \$108.06 billion (as described in section 3.5) to \$104.49 billion. A change in the generation mix vis-à-vis case A is noticed – more wind generation is built in the high-wind areas of northern and western Iowa and less natural gas-fueled generation is built, with transmission expansion towards the load centers. Figure 5.3 shows a visual corresponding to year 2036 for this case.

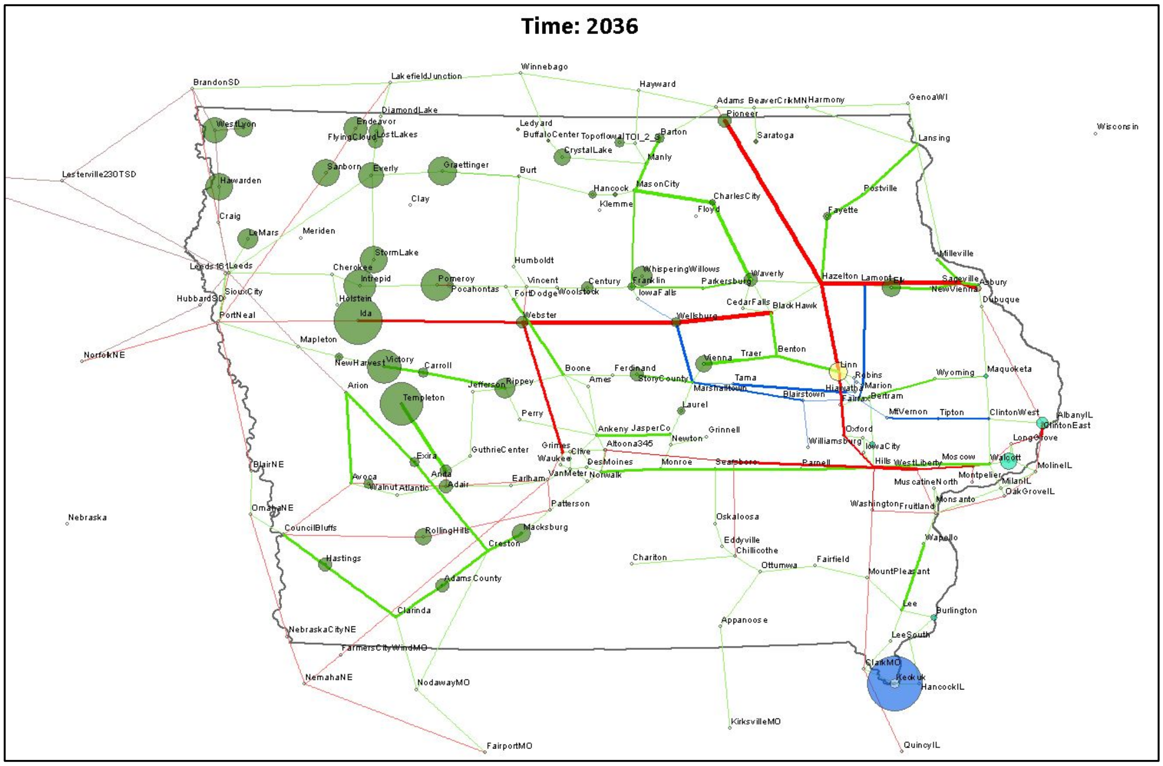


Figure 5.3 Illustrating the value of transmission - Year 2036

5.2. Comparison of Results

The tables below tabulate results from both the cases for ease of comparison. Table 5.1 shows generation capacity builds, Table 5.2 shows generation capacity retirements and Table 5.3 shows cost comparisons between both cases.

Table 5.1 Comparison of generation capacity builds

Generation Technology	Case A Builds (MW)	Case B Builds (MW)
Wind	20000	25149.57
Gas – Combustion Turbine	2897.05	460.63
Gas – Combined Cycle	7903.63	5144.47
Coal	0	0

Table 5.2 Comparison of generation capacity retirements

Generation Technology	Case A Retirements (MW)	Case B Retirements (MW)
Wind	1392.88	0
Gas – Combustion Turbine	1879.36	1040
Gas – Combined Cycle	1518.6	1518.6
Coal	6112.8	6112.8

Table 5.3 Comparison of capital investments and costs

Cost Component	Case A Cost (2016 $)	Case B Cost (2016 $)
Gen. capital investment	$48.88 billion	$56.92 billion
Generation fixed O&M	$19.41 billion	$22.35 billion
Generation variable O&M	$3.57 billion	$1.23 billion
Generation fuel cost	$21.49 billion	$8.80 billion
Generation carbon tax	$30.66 billion	$10.65 billion
Trans. capital investment	None	$4.51 billion
Total cost	$124.01 billion	$104.49 billion

Cost-wise, case A will cost $19.52 billion more than case B, in spite of being just a generation expansion plan. The generation mix in case A indicates that the wind generation in case B is replaced with natural gas plants, thus getting a lower generation capital investment cost but much higher operational and carbon costs. Total variable O&M costs and fuel costs are more than double of those in case B and the carbon cost is almost three times the carbon cost in case B due to greater penetration of natural gas-fueled generation in case A. All coal generation is retired within the first few years of the planning horizon in both cases, though in case A, it is retired later than in case B. High operational and fuel costs, coupled with increasing carbon taxes and high carbon dioxide emission rates make coal plants economically unviable to operate in the long run, compared to other technologies.

Evidently, case B prefers building cheaper, environment friendly wind generation in areas with a high wind capacity factor, simultaneously expanding the transmission infrastructure necessary towards the load centers, as against building more expensive natural gas-fired generation closer to the load centers. This study leads us to believe that the value of transmission is at least \$19.52 billion over a period of 20 years (a savings of 15.74% over case A), reinforcing the significance of investing in transmission to meet future electric energy needs in a cost-effective manner.

CHAPTER 6. SUMMARY AND SCOPE FOR FUTURE WORK

In a high wind penetration scenario, co-optimized generation and transmission planning is a necessity to ensure that the economics of simultaneous rapid growth in wind energy production and the presence of sufficient transmission infrastructure is efficiently achieved. The potential to visualize the results easily using GIS will provide a convenient platform for planners to analyze and explore complex decision trajectories to aid the planning process for the future of Iowa's electric power system.

6.1. Overview of Results

In this attempt to run and visualize co-optimized expansion planning for Iowa, a 20 GW high wind penetration future was considered for a 20 year planning horizon (2016 – 2036).

A suitability analysis tool to identify or eliminate candidate wind farm sites based on their potential feasibility or absolute infeasibility was developed using ArcGIS. These candidate wind sites, along with candidate combustion turbine and combined cycle gas plants, transmission candidates, Iowa power system topology, planning assumptions, demand and cost data (outlined in chapter 3) were provided to the Co-optimized Generation and Transmission Expansion Planning software (CGT-PLAN), formulated and coded in GAMS. The LP optimization problem identified generation and transmission investments within the same optimization problem, which was run using CPLEX, and the results were visualized using a Python interface in ArcGIS.

The results identified almost 25 GW of wind generation in Iowa for the given assumptions, together with some natural gas plant builds. Wind generation was mostly built in the high wind resource areas of northwestern and western Iowa. Carbon taxes and high coal fuel prices led to all coal generation being retired during the planning horizon. Transmission investments were commensurate with generation investments, with transmission being strengthened from new generation sources towards loads in the east and south.

A study comparing a generation expansion-only case with results of CGT-PLAN emphasized on the value of transmission and made a point about how investing in new line infrastructure helps in reducing overall cost by offsetting the need to build more amount of localized generation.

Leveraging a Geographic Information System in the expansion planning process assisted in a quick, convenient comprehension of planning results, making it easier to communicate the plans to stakeholders in terms of a visual representation of the most cost-effective new generation and transmission investments.

It is imperative to note that the results in this work correspond to one set of planning assumptions. Changes made to the assumptions might potentially result in the software investing in a very different generation mix and transmission topology. The strength of leveraging GIS lies in this very ability to analyze and discern such patterns in an efficient manner for several such results, helping a planner to better understand and choose the optimum plan.

6.2. Scope for Future Work

This thesis focuses only on co-optimized expansion planning for the state of Iowa. A similar model can be used to run an expansion plan for the entire MISO region, or even for the eastern interconnection, with appropriate modifications. A larger scale of planning will impart a bird's eye view of the requirements of the region as a whole and help in understanding how generation and transmission resources in different states can contribute to the overall adequacy of the grid.

An analysis of the stability and reliability concerns may be carried out to ascertain whether such issues, which cannot be identified in capacity expansion plans, can be identified.

The model used in this project is strictly deterministic. Future work can include a provision for an element of uncertainty which might generate more realistic scenarios and results.

Only a fraction of the potential of ArcGIS has been utilized in this work. Its applications can be extended to micro-siting wind turbines and transmission infrastructure, and to visualize cost data over the planning horizon. The tool to identify candidate wind farms and the visualization capability developed for expansion planning results can also be extended to other similar projects.

APPENDIX CHARACTERIZATION OF IOWA POWER SYSTEM

In this appendix, input data characterizing the Iowa power system is described, including operational parameters for existing and candidate generation, operational parameters for existing transmission and investment parameters for candidate generation and transmission. Assumptions and approximations in the dataset which were not discussed in section 3.3 are also presented here.

A.1. System Topology

The Iowa power system was developed using various sources such as a dated map from 1984 by the Iowa Utilities Board, a digital copy of which was obtained from Iowa State University's GIS repository. Recent MISO Transmission Expansion Plan (MTEP) documents, data from the U.S. Energy Information Administration (EIA) state profile for Iowa and news reports were also used in assembling a reasonable model for the Iowa power system [3][28][29].

Data for existing generation was gathered from the EIA state profile for Iowa. A list of conventional generation and wind generation in Iowa as of December 2015 is shown in Table A.1 and Table A.2, respectively. Planned retrofits from coal-fired to natural gas are shown in Table A.3 [30]. Two natural gas power plants which have reached the end of their lifespan are scheduled to retire, listed in Table A.4.

Table A.1 Existing conventional generation in Iowa

Name	Type	Capacity (MW)
Electrifarm	cc	264.1
SummitLake	cc	75.4
GreaterDesMoines	cc	576.3
RoquetteGas	cc	48
EmeryStation	cc	602.8
AmesMunicipalPowerPlant	coal	108.8
IowaStateUniversity	coal	46.2
ArcherDanielsMidland	coal	7.9
Burlington	coal	268.3
StreeterStation	coal	49.4
UnivofNorthernIowa	coal	7.5
ArcherDanielMidlandCedarRapids	coal	260
PrairieCreek	coal	198.8
Ottumwa	coal	746.3
ArcherDanielsMidlandClinton	coal	180
UniversityofIowaMain	coal	30.7
WalterScottJr34	coal	1648.3
CargillCornMillingDivision	coal	40
Lansing	coal	274.5
Louisa	coal	805.8
MuscatinePlant1	coal	250.5
GeorgeNealNorth	coal	549.8
GeorgeNealSouth	coal	640
Dubuque	ct	71.8
AtlanticMunicipal	ct	13.8
GasTurbine1	ct	34
RiverHills	ct	116.9
AgencyGT	ct	57
MerleParr	ct	32.6
NewHampton	ct	24.1
Osage	ct	16.8
MiltonLKapp	ct	218.5
CoralvilleGT	ct	72
Riverside	ct	136
EarlFWisdom	ct	37
Exira	ct	139.5
Grinell	ct	44.6
Sycamore	ct	170
Maquoketa1	ct	26.6
RedCedar	ct	13.9
Sutherland	ct	119.1
CargillMonroe	ct	40
PleasantHill	ct	179.8

Table A.1 continued

NorthPlant	ct	20.4
KeokukHydro	hydro	140.5
DuaneArnoldEnergyCenter	nuclear	601.4
AmesGT	petrol	22
Centerville	petrol	53.6
ForestCity	petrol	22
Algona	petrol	21.6
Shenandoah	petrol	20
Spencer	petrol	23.8
Independence	petrol	22.9
RoquettePetrol	petrol	32
Marshalltown	petrol	202.2
LimeCreek	petrol	82.8
MountPleasant	petrol	32.5
Indianola	petrol	54.8
PellaPeaking	petrol	28
WebsterCity	petrol	25.5

Table A.2 Existing wind generation in Iowa

Name	**Type**	**Capacity (MW)**
Adair	wind	174.8
MorningLight	wind	101.2
Adams	wind	154.3
Barton	wind	160
LittleCedar	wind	1.5
IowaLakesLakota	wind	10.5
IowaDistributedWindGeneration	wind	2.3
Carroll	wind	150
Century	wind	200
CerroGordo	wind	42
CharlesCity	wind	75
CrystalLake	wind	416
Winnebago	wind	20
Eclipse	wind	200.1

Table A.2 continued

ElkWind	wind	40.8
Endeavor	wind	150
Sibbley	wind	5.4
Hawkeye	wind	34
FlyingCloud	wind	43.5
IowaLakesSuperior	wind	10.5
FranklinCounty	wind	99
Crosswinds	wind	21
HancockCounty	wind	98
Intrepid	wind	175.5
Laurel	wind	119.6
LakotaKossuth	wind	10.5
LostLakes	wind	100
Macksburg	wind	119.6
NewHarvestCrawford	wind	100
PrairiePioneer	wind	300
PocahontasPrairie	wind	80
Pomeroy	wind	286.4
HardinHilltop	wind	14.8
Rippey	wind	59
RollingHills	wind	443.9
HighlandWind	wind	502
CraneCreek	wind	29
StormLake	wind	189.6
StoryCounty	wind	300
Templeton	wind	20
TopofIowa	wind	189.7
Victory	wind	99
Vienna	wind	150.2
Walnut	wind	153
Waverly	wind	2.7
LundgrenMidAmerican	wind	251
Wellsburg	wind	140.8
WhisperingWillows	wind	199.7

Table A.3 Planned Retrofits

Name	**Type**	**Retrofit Year**	**Capacity (MW)**
Burlington	coal	2021	268.3
PrairieCreek	coal	2025	198.8
AmesMunicipalPowerPlant	coal	2017	108.8

Table A.4 Planned Retirements

Name	**Type**	**Retirement Year**	**Capacity (MW)**
Dubuque	ct	2018	71.8
Sutherland	ct	2018	119.1

A.2. Generation Parameters

Parameters for existing and candidate generation were approximated based on data obtained from EIA [43]. Generation parameters used are shown in Table A.5. Overnight costs for building new generation were also obtained from the EIA, shown in Table A.6.

Table A.5 Generation parameters

Generation technology	**Installed Capacity (MW)**	**Fixed O&M Cost ($/kW-yr)**	**Variable O&M Cost ($/MWh)**	**Heat Rate (MMBtu/MWh)**	**Carbon Emissions (lb/MMBtu)**
Pulverized Coal	6112.8	48.22	4.47	10428	207.9
Natural Gas - Combined Cycle (CC)	1566.6	14.39	3.60	7050	116.7
Natural Gas - Combustion Turbine (CT)	1584.4	16.62	8.31	8185	116.7
Wind	6245.9	34.22	0	N/A	N/A
Petroleum	643.7	16.74	3.21	10814	161.3
Nuclear	601.4	112.77	2.04	10459	N/A
Hydro	140.5	14.24	0	N/A	N/A

Table A.6 Overnight Capital Costs for building new generation

Generation technology	**Overnight Capital Cost ($/kW)**
Wind	2644
Natural Gas - CC	1080
Natural Gas - CT	707

The generation mix consisted of coal-fired, natural gas (combustion turbine and combine cycle), petroleum, nuclear, hydro and wind units. Only wind and natural gas-fired generation was allowed to expand. The petroleum units were almost never dispatched because of how expensive they were to operate.

The lone hydro power plant in Keokuk was dispatched with a capacity factor of 40%. Capacity factors for wind varied by location, in the range of 25% to 45%, with larger values expected in the future depending on technology maturation and location. Wind generation is also assigned a capacity credit of 15% for contribution to system reliability [44].

Fuel prices were obtained from EIA estimates. Values used were \$2.25/MMBtu for natural gas, \$2.18/MMBtu for coal and \$13.47/MMBtu for petroleum [45][46]. The fuel prices were increased at a rate of 1% every year.

A.3. Transmission Parameters

For the transmission topology, lines with voltage at or above 115kV were considered, with four voltage classes in Iowa – 115kV, 161kV, 230kV and 345kV. Since a pipes and bubbles model is used to represent candidate transmission, no reactances were assigned to them. Expansion costs were calculated in terms of \$/kW assuming an average line length of 80 miles. These costs are approximate, based on costs observed in the Eastern Interconnection Planning Council (EIPC) Phase-1 assumptions and MISO's MTEP reports [47]. Transmission expansion costs are shown in Table A.7.

Table A.7 Transmission Expansion Costs

Transmission Level	**Expansion Cost ($/MW-mi)**
115kV	1288
161kV	1025
230kV	1300
345kV	2625

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