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Modeling and analysis of EPA emission regulations on US generation portfolio

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LIST OF ACRONYMS

CCS	Carbon Capture And Sequestration
CO_2	Carbon Dioxide
CATR	Clean Air Transport Rule
CCR	Coal Combustion Residuals
CDS	Coal Distribution Sub Module
CMM	Coal Market Module
CPS	Coal Production Sub-Module
DOE	Department Of Energy
DTS	Distributor Tariff Sub-Module
ELCC	Effective Load Carrying Capacity
ECP	Electricity Capacity Planning
EFP	Electricity Finance And Pricing
EFD	Electricity Fuel Dispatch
EMM	Electricity Market Module
EUE	Expected Unserved Energy
FGD	Flue-Gas Desulfurization
FES	Fuel Economy Sub-Module
GA	Genetic Algorithm
GHG	Greenhouse Gas
IGCC	Integrated Gasification Combined Cycle
IPM	Integrated Planning Model
LDVS	Light-Duty Vehicle Stock Sub-Modules
LP	Linear Program
LDC	Load During Curve
LMP	Locational Marginal Pricing
LOLE	Loss Of Load Expectation
LOLP	Loss Of Load Probability

MAM	Macroeconomic Activity Module
MACT	Maximum Achievable Control Technology Standard
MARKAL	MARKet ALlocation
Hg	Mercury
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
NG	Natural Gas
NGTDM	Natural Gas Transmission And Distribution Module
NPV	Net Present Value
NFLP	Network Flow Linear Programming Model
NO_X	Nitrogen Oxides
NERC	North American Electric Reliability Corporation
PMM	Petroleum Market Module
PTS	Pipeline Tariff Sub-Module
PTDF	Power Transfer Distribution Factor
ReEDS	Regional Energy Deployment System
RSS	Regional Sales Sub-Module
RFM	Renewable Fuels Module
RPS	Renewable Portfolio Standard
SCED	Security Constrained Economic Dispatch
SCUC	Security Constrained Unit Commitment
SCR	Selective Catalytic Reduction
SO_2	Sulfur Dioxide
ITS	The Interstate Transmission Sub-Module
TRAN	Transportation Demand Module
EPA	US Environmental Protection Agency
VRRE	Variable Resource Renewable Energy
VMTS	Vehicle-Miles Traveled Sub-Module

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ABSTRACT

The first objective of this thesis is to assess NETPLAN effectiveness as a new planning tool for meeting the requirements of power system planning. The second objective is extension of NETLAN so that it can analyze the impact of existing and proposed EPA regulations on generation portfolios during the next 40 years.

In the first half of the thesis, NEPLAN, NEMS (DOE), and ReEDs (NREL) are introduced. Comparisons among the three models include model design, solution approach, energy and transportation systems elements, objective function, and constraints in the Linear Programming problem. Based on the model comparison, the strengths and weaknesses of NETPLAN, NEMS (DOE), and ReEDs (NREL) are discussed. NETPLAN is assessed as an effective new tool for power system planning due to its uniqueness in multi-sector, multi-objective design.

In the second half of the thesis, NETPLAN is improved to enable analysis of impact of proposed environmental regulations. Compliance strategies include establishing new power plants with low emission rates, retrofitting with emission control equipment, modified dispatch strategies, fuel switching, and earlier retirement. A multi-level and multi-arc design approach is applied to model power plants retrofitted with emission-control equipment. Scenarios are developed for examining the impact of existing and proposed environmental regulations. NETPLAN results are compared with research results from NEMS (DOE), ReEDS (NREL), and NERC. The case study results demonstrate an increased need for using natural gas and renewable energy resources to meet environmental regulations.

CHAPTER 1: INTRODUCTION

1.1 Background

The thesis is based on two PhD dissertations done by Dr. Ana Quelhas[1] and Dr. Eduardo Ibanez[2]. Dr. Quelhas put forward a model that integrates different energy systems into a single analysis framework. The idea was based on the observation that no electric power operation and planning models had been developed and operated for a national level fuel-electric system, even though modeling fuel supply resources and electric transmission grids could provide a broader view of system interconnection. Dr. Quelhas applied a generalized network flow algorithm representing energy flows through paths of an integrated network, making it possible to combine and analyzed is joint energy systems as one generalized, multi-period, and minimum-cost flow problem.

Dr. Ibanez expanded Dr. Quelhas's work into a long-term joint investment model by adding non-energy transportation systems. He also implemented software NETPLAN using C++, and ILOG CPLEX.NETPLAN separates model parameters and network definition from the source code, allowing further development of new features based on the current network. Another improvement was to expand a single-objective linear program (LP) problem into a multi-objective optimization problem by introducing concepts of resiliency and sustainability. The NSGA-II algorithm[2]was applied to solve the multi-objective problem.

The idea of incorporating non-energy transportation systems into the original model is based on two main concepts. In 2008, electrical and transportation sectors in the United States consumed 69% of total U.S. energy, and74% of energy-related greenhouse gas (GHG) emissions came from the electrical and transportation sectors. These data suggest that a joint model including both transportation and electrical sectors could help to improve efficiency of energy usage and to reduce GHG emissions[3]. A joint-sector model would also reflect interdependencies between energy and transportation systems. Energy conversion industries like electrical power plants need transportation systems to transport source fuel to meet their energy production requirements. Increasing energy production and investment requires a corresponding investment in transportation systems. Failure to transport fuel because of transportation system constraints will lead to suboptimal operation of electrical systems and increase cost of energy production. Fuel transportation cost obviously translates into electricity price. Likewise, transportation systems require energy systems to provide different fuel types to support different fleet types. Fuel supply and price reflect transportation demand whether by air, rail, or highway. Another factor driving interdependencies between energy systems and transportation systems is existence of environmentally-oriented regulatory policies. Changing regulations encourage joint system planning leading to highly-efficient and low-emission energy and transportation systems[2][4].

The ever-changing situation challenges conventional energy-system planning that has typically been separated from transportation-system planning. A multi-objective model is needed to optimize long-term investment for joint energy and transportation systems for the following reasons. First, both energy and transportation systems are capital-intensive. Once infrastructure is build, it usually expected to last for twenty years or even much longer. As a result, initial investment will significantly influence consequence investment. Therefore, long-term investment planning producing relatively accurate decisions are needed to avoid possibly ruinous financial loss [4]. Second, environmental concerns drive energy policy-makers to encourage use of renewable energy sources and electrified transportation system development. The integration of intermittently-available renewable energy requires flexible, cost-effective generation to meet power system reliability standards. Economic, environmental, and reliability requirements challenge system planners to meet necessary multiple objectives. To help planners meet this challenge, NETPLAN includes operational cost, emission, and reliability in its multi-objective model to produce a long-term investment plan targeting cost-effective, sustainable, and resilient systems.

1.2 Objectives

This thesis has two objectives, the first being to compare NETPLAN with a national energy-modeling system (NEMS)[5] and a Regional Energy Deployment System (ReEDS)[5],both of which have functions comparable to those of NETPLAN. NEMS is an energy economy model that has a capacity expansion-planning model within its electrical market module. It is also a multi-sector model that includes both energy and transportation systems sectors, a feature found in few existing energy models, an exception being MARKet Allocation (MARKAL) [3]. ReEDS is a resource and transmission planning model developed by the National Renewable Energy Laboratory (NREL). Its main feature is its ability to deal with variability and uncertainty of intermittently-renewable energy like wind and solar energy. ReEDS addresses transmission and storage issues related to intermittent renewable energy. The model comparison provides us with information for further improving NETPLAN, and advantages and disadvantages of NETPLAN are given based on the model comparison. The uniqueness of NETPLAN is stated to show that NETPLAN is essential and contributes to understanding of long-term energy and transportation systems planning.

The second objective of this thesis is to extend the NETPLAN model to account for decision-making in coal power plants under US Environmental Protection Agency (EPA) regulations. Emission constraints, including both SO_2 and NO_X caps at the national and regional level, are modeled. Emission-control equipment, such as a Flue-Gas Desulfurization (FGD), a Selective Catalytic Reduction (SCR), and a Carbon Capture and Sequestration (CCS), are implemented as options in this model for controlling emission. Design of fossil-fuel power plants should reflect choice of various compliance strategies, including investment in new power plants with low emission rates, retrofitting emission-control equipment in existing power plants, changing dispatch strategies, switching fuel types, and early plant retirement. The improved model can be used to analyze the impact of existing and proposed EPA regulations on the generation portfolio for a given planning horizon. Sensitivity analysis can determine the impact on generation portfolios of changes in investment cost, maximum investment capacity, and carbon tax.

1.3 Current Planning Tools

There are three main types of planning tools for electrical infrastructure: reliability, production cost, and resource optimization[3]. Although the model discussed in this thesis is largely a resource-planning tool, reliability and production cost are also introduced to enable the optimization tool to evaluate production cost and assess system reliability. Other deterministic tools, including power flow, stability, and short-circuit programs, are used for system planning and operation. For planning activities, these tools are used to check to see if an existing or planned system could operate without violation under normal or contingency conditions over the planning horizon.

Probabilistic tools evaluate system reliability by computing reliability indices such as loss-of-load expectation (LOLE), loss-of-load probability (LOLP), or expected unserved energy (EUE) based on certain generation and transmission infrastructures and scenarios[3]. They usually begin with selecting either sequential or non-sequential operating conditions. Either an Enumeration or a Monte-Carlo method is used to select contingencies. In a case where the selected contingency causes system problems such as power-flow violation or voltage violation, generation linear programming of re-dispatch and reactive support are performed to relieve the contingency. If no re-dispatch solution can solve the system violations, the reliability index is calculated. This calculation will be performed until the program goes through all operating conditions and contingencies.

Production cost tools determine the annual production cost of producing energy for the entire 8760 chronological hours constituting each year [3]. Security constrained unit commitment (SCUC) and security constrained economic dispatch (SCED) are optimized subject to generator-operation and transmission-line constraints. Generation expansion, generation unit characteristics (operating constraints, outage and costs), and transmission grid topology and constraints must be determined before running the production cost tools. The output of production cost tools includes generation capacity factors by type, branch power flow, congestion, and market prices. Production cost tools such as PROMOD can calculate cost/benefit ratios based on the locational marginal pricing (LMP), which is used to assess economic benefit derived from new transmission line construction.

Resource-planning models determine power generation investments subject to constraints due to load demand, environmental concerns, transmission, and reliability levels[3]. Resource-optimization models apply linear programming algorithms to select required minimum cost investments from a range of technologies. Most of these tools (except PLEXOX [7]) do not optimize transmission investments. However, integrating transmission planning with resource planning is a meaningful objective for planners to study. There are a number of relationships between the three types of planning tools. On the one hand, reliability tools and production cost tools need generation and transmission expansion estimates from the resource planning process. On the other hand, production cost programs usually briefly incorporate reliability evaluation. Resource optimization models usually incorporate simplified production-cost evaluation, including reliability evaluation.

Since greenhouse gas (GHG) emissions and renewable resources have begun to draw more and more attention, resource planning tools are implemented to address these kinds of issues. Typical examples include Integrated Planning Model (IPM) [8] and the Regional Energy Deployment System (ReEDS).

The Integrated Planning Model (IPM) is a linear programming model of resource planning developed by the U.S. Environmental Protection Agency. It stresses the national-level impact of environmental policies on generation portfolios. The IPM provides least-cost capacity expansion, electrical dispatch, and emission-control strategies to meet energy demand and environmental, transmission, dispatch, and reliability constraints. The emission limits in IPM include sulfur dioxide (SO_2), nitrogen oxides (NO_X), mercury (Hg), and carbon dioxide (CO_2) from the electrical power sector[8].

The Regional Energy Deployment System (ReEDS) is a resource-planning model developed by the National Renewable Energy Laboratory (NREL). The main purpose of ReEDS is to minimize the total cost of the electrical sector subject to renewable capacity installation, transmission, and operating constraints that take into account the effect of renewable energy. It creates 356 specific renewable-energy supply/demand areas. Wind resources are divided by 5 classes and 3 types. Wind-supply curves are created for each wind class, each type of wind resource, and each region. Parameters such as capacity factors and capacity values are used to represent the variability of intermittent renewable resources[5].

The tools described above have one deficiency in common; none of them is a multi-sector model. "Multi-sector" refers to the ability of a model to address more than just the energy sector of the economy" [3]; Only two existing tools can be called multi-sector models: the National Energy Modeling System (NEMS), and MARKAL/TIMES. We will describe NETPLAN and NEMS in detail in the following chapters.

NEMS belongs to the class of energy economy models that aims to simulate interaction between the macro-economy and the energy sector. NEMS includes calculation of and limits on emission, so is also a 3E (energy, economy, and emission) model[9]. NEMS represents the electrical supply, petroleum, natural gas, coal, and transport /transmission sectors coupled with interactions among macroeconomic, domestic energy, and international energy activities [5].It is an equilibrium model that balances energy demand and energy supply. Policymakers and planners may use NEMS to analyze the potential impact of energy and/or environmental policy changes on different energy and economic sectors. Decision makers may find these investment strategies useful in making their decisions. In NEMS, a resource planning model is embedded in the electrical market sector. There is information flow among the electrical, coal, natural gas, petroleum, and renewable-resource sectors. For example, the electrical sector provides fuel demand to the fuel-supply sector, and the fuel supply sector provides fuel price and supply to the electrical sector.

MARKAL/TIMES provides an understanding of the interplay between the macroeconomic and energy use. It is a single-optimization model that aims to supply energy resources at minimized cost. At the same time, it provides decisions on equipment investment, equipment operation, and energy trade. MARKAL/TIMES represents energy resources, including petroleum, natural gas, coal, and electrical sectors. Transportation costs associated with these energy sectors are, however, not represented**Error! Reference source not found.** [9].

1.4 Organization

This thesis consists of 7 chapters. CHAPTER 1 describes how NETPLAN represents energy and transportation sectors in a network-flow linear-programming model (NFLP) and describes the underlying mathematical formulation and algorithms of the model. CHAPTER 2 introduces NEMS and ReEDS and describes in detail the energy and transportation sectors and treatment of intermittent renewable energy. Based on the material of CHAPTER 1 and CHAPTER 2, CHAPTER 3 gives comparison summaries among NETPLAN, NEMS, and ReEDS. Possible improvements of NETPLAN based on these comparisons are also presented, along with a summary of advantages and disadvantages of NETPLAN, NEMS, and ReEDS. CHAPTER 4 summarizes EPA existing and proposed regulations which may have impact on fossil fuel power plants. CHAPTER 5 describes the implementation of the proposed environmental regulations modeled in NETPLAN. CHAPTER 6 provides a corresponding case study using the improved model. CHAPTER 7 concludes with the findings and observations of the research.

CHAPTER 2: SUMMARY OF NETPLAN

2.1 NETPLAN Overview

NETPLAN is a long-term multi-objective investment planning model used to find a national-level optimal investment solution for combined energy and transportation systems.

NETPLAN is a long-term planning model with a 40-year time horizon. It includes both energy and transportation systems. The electrical power system is the main component of the energy system, and it uses both traditional energy sources (coal, natural gas, petroleum, uranium) and renewable sources (wind, solar, biomass, water behind dams, tides). Power plants and transmission tie lines are the main components of the electrical systems. Coal transportation and natural gas pipelines are also included to represent the fuel supply and transportation system. The non-energy-related transportation system is represented by freight and passenger transportation along with transportation modes (train, highway and water) and fleets (light duty vehicle, truck) to reflect fuel demand, CO_2 emission, and transportation electrification.

The multiple objectives of NETPLAN include minimum cost, maximum sustainability, and maximum resilience. A linear programming (LP) model is used to set up the minimum-cost problem. The objective function of the LP model includes both investment and operating costs so that a tradeoff between the two kinds of costs could be determined. The input data for the LP model includes energy demand, existing energy and transportation infrastructure, fuel production cost, transportation cost, investment cost of different technologies, and operational costs. The output of the LP model includes energy flow and required investment for both the energy system and the transportation system. Resilience and sustainability are used to provide a Pareto Front [2]so that compromises among the three different objectives could be made.

One significant feature of NETPLAN is that the network-flow LP model (NFLP) [10]is introduced into the cost-minimization LP model. The network-flow LP model is a special case of the more general linear programming model. It is constructed as a set of nodes and arcs, with commodities flowing along arcs that connect nodes. There are several benefits to applying the NFLP in NETPLAN. First, electrical and transportation systems can be suitably represented in the arcs-and-nodes structure. Second, by using the NFLP, the arcs-and-nodes system is more easily understood so that the model has clear physical meaning. Third, there is a mature solution method for solving the NFLP model and experience shows that it is twice as fast as the general LP method [1].

There are four types of nodes in NETPLAN [2]. Supply nodes serve to represent the production of raw energy forms (coal and natural gas); Demand nodes represent the demand of energy (electricity and natural gas); Trans-shipment nodes are used to represent energy conversion or energy transmission, where the incoming energy at a node is equal to the energy leaving it. Energy conversion is made at trans-shipment nodes representing power plants energy sources like coal and natural gas are converted into electrical energy; Storage nodes are used to interconnect time steps and allow energy flow between consecutive points in time. Attributes associated with the nodes include demand, peak load, and unserved demand.

Arc representation in NETPLAN depends on the types of nodes they connect. When origin and destination nodes belong to the same subsystem, arcs are used to represent transmission lines, natural gas, or petroleum pipelines. When origin and destination nodes connect two different networks, arcs are used to represent conversion between energy types. For example, arcs that represent coal-power plants connect coal trans-shipment nodes and electrical-demand nodes. Arcs between two consecutive time periods represent storage injections, withdrawals, or inventories. Arc attributes include maximum operating capacity, production cost of raw energy sources, operation and maintenance costs, investment costs, maximum (minimum) investment capacity, and efficiency (loss in gas transportation and electrical transmission).

Flows are the representation of commodities moving along the arcs in a NETPLAN network. Energy is the only flow along the arcs connecting nodes. In a NFLP model, flows and investment variables are decision variables.

There are restrictions to ensure that the node-arc network has physical meaning. For example, energy flow should not exceed the current capacity of an arc. Energy flow entering a node must equal the total flow leaving the node. In pure minimum-cost flow problems, the matrix that describes these constraints on the node-arc network turns out to be a sparse matrix characterized by, at most, two non-zero elements in each column. These non-zero entries are either +1 or –1. The matrix, in the terminology of NFLP, is a call node-arc incidence matrix[10].

NETPLAN produces a 40-year plan in one simulation. Figure 2-1[2]illustrates the concept of the multi-step approach used in NETPLAN. "The multi-period network flow models may be viewed as a composition of multiple copies of a given network, one copy for each point in time, with arcs that link these static snapshots describing temporal linkages in the system. Different time steps are used to avoid unnecessary detail of other systems represented. The electrical subsystem time step is hourly, the most frequent. The natural gas system is the next most frequent, and it could be monthly. The coal subsystem uses the slowest frequency, e.g., yearly [2]".

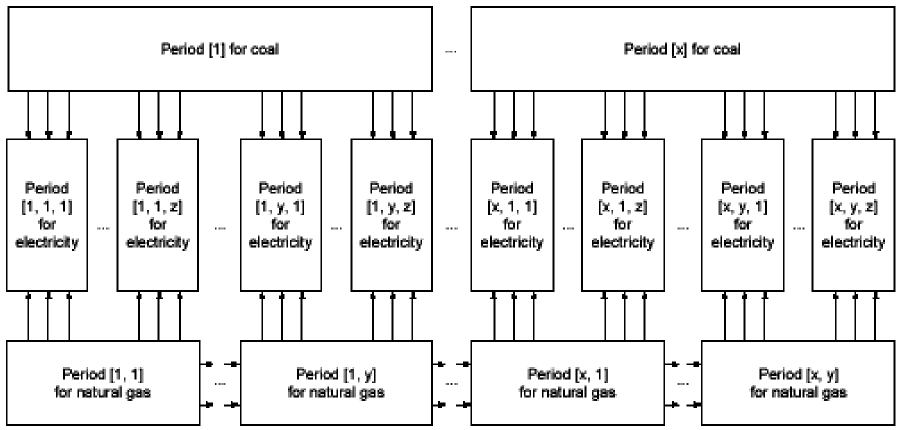

Figure 2-1. Model dynamics and multi-step approach

2.2 Energy Sectors in NETPLAN

One of the main tasks of setting up a NFLP model is to transform elements of the electrical and transportation systems into the arcs-and-nodes format.

2.2.1 Electric System

Electricity demand: Electricity demand is assigned to the electricity demand node. Similarly, the natural gas (NG) demand is assigned to the natural gas demand node. In NEPLAN, electricity demand is represented as energy (MWh) instead of power (MW). A load-during curve (LDC) is used instead of a load curve to avoid highly-intensive computations. Energy (MWh) is obtained by multiplying power demand (MW) by a time interval in the LDC curve.

Load duration curve: The load-during curve is divided vertically into several pieces so that electricity demand (MWh) can be determined. Each piece of the LDC represents a time slice.

All the time slices are solved simultaneously in the NFLP model. For example, if each year's LDC is divided into 3 pieces, for a 40-year horizon there should be 40×3 time slices.

Power plants: power plants are modeled as trans-shipment nodes, with one arc connected to electrical demand nodes and the other connected with fuel-transportation nodes. One power plant node could be split into two or more nodes so that more arcs could be added to represent its particular characteristics. For example, multiple arcs could be used to model piecewise-linear concave function for heat rate segments. Parameters assigned on the power plant arc include the heat rate and emission rate, maximum operational capacity, operational and maintenance costs, investment costs, and capacity credits.

Transmission lines: Transmission lines are modeled as arcs. There are two types of transmission lines in NETPLAN. One type is the tie line connecting two control areas, while the other is a transmission lines within a control area. The difference between these two types of transmission lines is that the arc flows on tie lines are decision-variables since it is possible to schedule flow across a tie line. This differs from arc flows in transmission lines within a control area that cannot be considered decision variables because they are determined according to Kirchhoff's laws. Parameters assigned to the arcs could be transmission efficiency, lower and upper bounds for power flow, minimum and maximum allowed capacity increase, and investment cost for increasing arc capacity.

2.2.2 Coal System

Coal supply: Coal supply is represented as a supply node. Four different type of coal are represented and identified by region, heat content, and emission rates. Parameters assigned to the supply nodes represent fuel-production quantity. Coal production costs (extraction and processing charges) are associated with outgoing arcs from the coal supply nodes. These outgoing arcs connect the coal-supply nodes, which in turn connect with nodes of the transportation system.

Coal transportation: Coal is mainly transported by railroad. A nodal demand model is used to represent the coal transportation system. Coal is assumed to be transported throughout the railway system. Coal-transportation rates can be obtained by multiplying the unit transportation cost with the transportation distance. For each node in a coal-transportation system, coal injections must equal the sum total of coal consumption and transportation to other nodes.

In NETPLAN, a fuel-transportation system connects fuel-production and power plants. Fuel can be transported throughout the fuel-transportation system so long as transportation constraints are not violated. Power plants may use either local fuel supply or fuel from remote sites, or both, at minimum cost.

2.2.3 Natural Gas System

Natural gas supply: Similarly to coal supply, natural gas supply is represented as supply nodes with outgoing arcs connecting to the natural gas pipeline system.

Natural gas pipeline: The natural gas transportation system is represented by a set of nodes and arcs. Natural gas demand is specified at the natural-gas demand node. Although coal could be transported in multi modes, natural gas is transported only along natural gas pipelines, represented as arcs. Pipeline tariffs are assigned to the corresponding transportation arcs.

Storage: Storage facilities are represented by arcs connecting different time steps from one period to the next. The amount of energy stored in the storage facilities are treated as decision variables in the network model and carried over from one period to the next. Parameters assigned to the arcs are maximum capacity and storage fees representing storage injections and withdrawals.

2.3 Non-Energy Related Transportation System

Introducing a non-energy related transportation system has the following benefits. First, it represents transportation needs from other departments, like freight and passenger. Second, additional transportation modes can be considered, since fuel for electrical systems may also be transported via highways and rivers. Third, transportation fleets can be modeled so that transportation capability can be represented in detail. It is also possible to model electrical demand due to use of electrical vehicles. Finally, transportation emission can be calculated according to vehicle type.

Transportation demand: non-energy-related goods are expressed as commodities (tons) or passengers (number of people). A link-demand model is used to represent the non-energy-related transportation system. In this model, commodity and passenger loading are treated as exogenous inputs specified on the arcs (routes). Transportation routes are predetermined outside the model.

Transportation modes: Although the shipment routes of non-energy-related commodities are not determined by the model, transportation modes need to be chosen in NETPLAN.

Transportation fleets: In transportation systems, there are several options for choice even for a single transportation mode. For example, for the highway transportation mode, the possible fleets include diesel trucks, ethanol trucks, and hybrid trucks.

Figure 2-2 [2] shows a multi-commodity flow network. Commodities may be transported by more than one transport modes (railway, highway, or river). Each transportation mode may use different fleet types (e.g., diesel trains or electric trains).

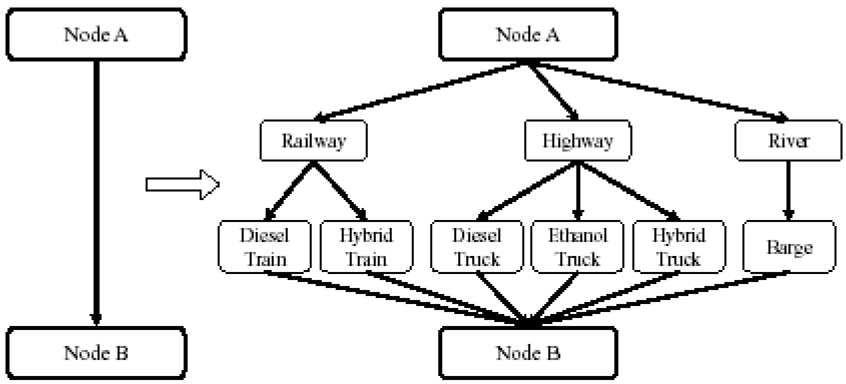

Figure 2-2. Decomposition of transportation arc in two steps: infrastructure and fleet [2]

2.4 Multi-objective Metrics in NETPLAN

The multi-objective metrics in the NETPLAN model involves a cost minimization LP model, a resiliency metrics and a sustainability metrics. Among the three objectives of the NETPLAN, minimum cost LP model is the core model, since the resiliency metrics and sustainability metrics use the output of the cost-minimization LP model to construct comprehensive indicators.

2.4.1 Cost-Minimization LP Model

The cost-minimization LP model is used to minimize various costs that occur during fuel transportation, electricity production, and power systems operational processes, while remaining subject to various constraints[2].Detailed descriptions of the variables and parameters in the NETPLAN model can be found in appendix A, while the objective function and constraints will be described in detail as follows:

Objective function

$$\min\{CostOp^E + CostInv^E + CostOp^T + CostFleetInv^T + CostInfInv^T\}$$

The objective function includes both investment costs and operational costs of the energy system, as well as both investment costs and operational costs of the transportation system. Investment costs of the transportation system are divided into fleet investment and infrastructure investment. Operational costs include fuel production costs, fuel transportation costs, fuel storage costs, electrical generation costs (operational and maintenance costs), and electrical transmission costs. Since both operational and investment costs are included in the objective function, a trade-off could be made between the two kinds of costs to minimize total cost.

Constraints

Meeting electrical demand at appropriate nodes

$$\sum_i \eta_{(i,j)}(t) e_{(i,j)}(t) - \sum_i e_{(j,i)}(t) = d_j^E(t) + d_j^{ET}(t), \qquad j \in N_d^E$$

$$d_j^{ET}(t) = \sum_{(a,b)\in A_j^T} \sum_{m\in M_j} fuelCons_{(a,b,m)}(t) \sum_k f_{(a,b,m)}(t)$$

In NETPLAN, the decision variables are energy flows $e_{(i,j)}$, transmission flows $f_{(i,j,k,m)}$, energy-capacity investment $eInv_{(i,j)}$, fleet investment $fleetInv_{(i,j,m)}$, and infrastructure investment $InfInv_{(i,j,l)}$. The energy sector is represented by a set of nodes N_E and a set of arcs A_E. The transportation system is also formed by a set of nodes N_T and a set of arcs A_T. (i,j) represents arc beginning and destination nodes.

This constraint ensures that energy supply flow is equal to energy demand at each demand node $j \in N_d^E$ of the energy system. For each time period t, the sum of the energy flow into node j and energy flow out of the node j must meet the energy demand at node j. η is the energy efficiency of energy arc (i,j) during time period t. For example, it could represent losses in the energy-conversion process at power plants. d_j^{ET} is the energy demand due to fuel required for the movement of commodities in the transportation system. It is measured by transportation flow for the commodity k using transportation mode m for arc (a,b) multiplied by the corresponding fuel consumption parameters.

DC power flow equations

$$e_{(i,j)}(t) - e_{(j,i)}(t) = b_{(i,j)}(t)\left(\theta_i(t) - \theta_j(t)\right) P_E \Delta(t), (i,j) \in A_{DC}^E$$

For energy flow along transmission lines within a control area, a DC power flow equation could be applied. Since NETPLAN represents energy in the format of MWh instead of MW, the DC power flow equation should be transformed to an energy flow equation. The left side of the equation is the energy flow, which could be bidirectional. The right side of the equation is multiplied by the power base and the time interval. It should be noted that the flows along the DC nodes set are determined according to Kirchhoff's laws. In contrast, the tie lines among NERC regions may be considered as decision variables whose flows can also be considered as decision variables.

Generation capacity must cover peak demand at electric nodes

$$\sum_i cf_{(i,j)}(t) eCap_{(i,j)}(t) \geq peakD_j^E(t), \qquad j \in N_p^E$$

This constraint ensures that generation capacity meets the summer peak load. For each electrical demand node$j$, the sum of the different energy resource capacity $Cap(i,j)$, multiplied by the corresponding capacity credit $cf(i,j)$,must equal total peak load demand at demand node j. For intermittent renewable energy such as wind energy and solar energy, different capacity credits may be assigned for different regions.

Transportation demand for non-energy commodities

$$\sum_{m} f_{(i,j,k,m)}(t) = d^{T}_{(i,j,k)}(t), \qquad k \in K \backslash K_e$$

This constraint ensures that freight transportation $f(i,j,k,m)$ must satisfy the transportation demandfor all commodities except for energy-related commodities. (i,j)represents origin and destination nodes. $k$is the commodity that is being transported. m isthe mode of transportation used.

Transportation demand for energy commodities

$$\sum_{m} f_{(i,j,k,m)}(t) = heatContent_k^{-1}(t) e_{\left(n^E_{(i,k)}, n^E_{(j,k)}\right)}(t), k \in K_e$$

This constraint ensures that energy-related transportation $f(i,j,k,m)$must satisfy fuel demand in the energy system. $k$represents different the kinds of energy related commodities. This could be coal or natural gas. $n^E_{(i,k)}$ represents the energy node at location i for commodity k. $e(n^E_{(i,k),} n^E_{(j,k)})$ is used to identify different energy flow arcs, since coal and natural gas are restricted to be transported via their own particular infrastructures, e.g., pipeline or railway. Parameter Heat Content is the heat content of commodity $k$that enables the conversion of different kinds of energy, such as, for example, from coal to electricity.

Fleet upper bound for transportation flows

$$\sum_{k} f_{(i,j,k,m)}(t) \leq fleetCap_{(i,j,k)}(t) \Delta t$$

Infrastructure upper bound for transportation flows

$$\sum_{k}\sum_{m\in M_l} f_{(i,j,k,m)}(t) \leq infCap_{(i,j,l)}(t)\Delta(t)$$

Transportation flows are constrained by the capacity of the available fleet $fleetCap_{(i,j,m)}$ and the capacity of the transportation infrastructure$infCap_{(i,j,l)}$. Both fleet and transportation infrastructure are allowed to be associated with upper-bound constraints.

2.4.2 Resiliency Metrics

"Resiliency is referred to the ability to minimize and recover from the consequences of an adverse event, whether natural or man-made, for a given state of the system"[11].

This definition depends on three basic concepts: states, events, and consequences. "States are defined as consisting of specification of the topology and operating conditions of the system. Events are the changes that may occur to the topology, to the operating conditions, or to both. Consequence refers to significant performance deviation of the system caused by the event"[11].

For electrical systems, events are the category B events [12]defined by North American Electric Reliability Corporation(NERC). For transportation systems, events may include accidents and weather-related closures. Reference [2] lists a number of event types that could be simulated to assess resiliency of energy and transportation systems. The sequence of events is measured in terms of increased operational costs or other related costs with respect to the base case.

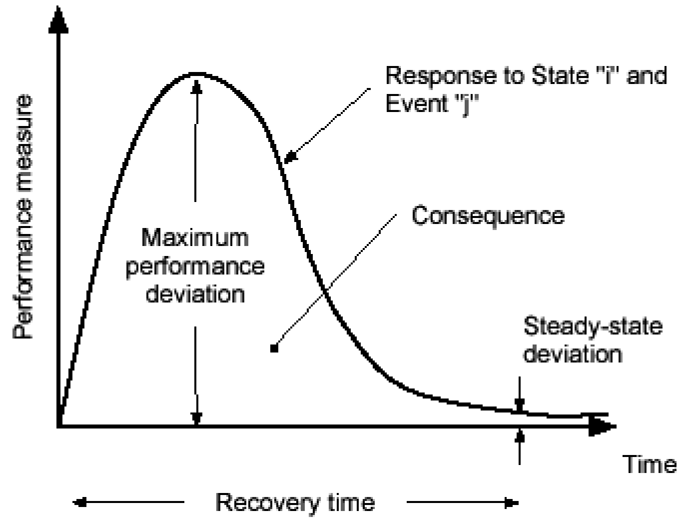

Figure 2-3. Illustration of resiliency measure for an event and state [2]

Figure 2-3 [2] illustrates the measurement of consequence with respect to state “i” and event “j”. The deviation performance is represented by the curve with long tail P(t). The end of the curve means system returns to the steady state. Therefore, the consequence is measured by

$$C_{ij} = \int_{o}^{\infty} P(t)dt$$

When there are more than one states or event, several consequences will be calculated. If we combine consequences together, this will enable determination of the differential degree of robustness of the system[11].

2.4.3 Sustainability Metrics

“Sustainability is defined as environmental impact and supply longevity”[13]. In NETPLAN, both energy and transportation systems are evaluated by a sustainability index that includes net emissions (CO, NO_X, SO_2, volatile organic compounds, CO_2), nuclear waste, water consumption, and resource displacement (e.g., land usage).

Each component of the sustainability index is calibrated by a linear expression. Sustainability expressions for air pollutants, water, land and depletable resources should not exceed a predetermined threshold, representing the environmental constraints in the model. These constraints are called side constraints since they may specify the relationships of flows along several arcs. A greenhouse emissions index used to compare solutions to projected trends has been developed. “This index identifies not only the global reduction but also encourages trends that reduce emissions over time [2].”

2.5 Algorithm Used to Solve NETPLAN

NETPLAN applies a network flow structure to set up the minimum-cost problem. The LP problem will become a partial-network flow problem if side constraints are added. Side constraints refer to constraints that add more restrictions on either total or partial energy flows [1]. With side constraints, energy flows will not only comply with the nature of the flow network but are also subject to other specific restrictions. As a result, the original pure network-flow problems become partial network problems which could be solved by ILOG CPLEX [14]. The network optimizer used in ILOG CPLEX will improve computation performance. For example, performance on a pure network problem could be 100 times faster using the network optimizer than using a simplex optimizer only [14]. For the partial network model, ILOG CPLEX could automatically recognize the network structure, solve this portion using the network simplex algorithm, and determine a network solution. Then, starting from a previous solution point, ILOG CPLEX will perform standard linear programming iterations on the full problem [1].

NETPLAN uses Benders decomposition method to speed up the LP solution time. The idea of Benders decomposition is to decompose the original LP model into one master problem and several sub-problems. When at least one sub-problem is infeasible, or variables are beyond limits, new constraints can be added to the master problem to get a new solution. The new solution is passed to the sub-problems to check if they are feasible or to see if variables are within limits. The master problem and the sub-problems will iterate until no further constraint are added to the master problem, producing the final solution. Since sub-problems are created to correspond to each planning year, these sub-problems can be solved in a parallel manner to further speed computation [2].

NETPLAN aims to provide insight into long-term investment planning with multiple objectives including cost, sustainability and resiliency. However, the linear programming (LP) solver can only solve a single LP model, so a multi-objective algorithm is used with the multi-objective model[15][16]. Figure 2-4 [2]illustrates the process via which a multi-objective approach can be made. First, a genetic algorithm is used to search and select solutions corresponding to new investment and energy flows. At each generation (iteration), evolution operations, such as crossover and mutation, are performed to obtain a better population to be used in the next generation. The selected solution will be passed to the LP model to provide a minimum-cost solution. After this solution is obtained, metrics of sustainability and resiliency are calculated. Sustainability is obtained from linear expression of all emissions. Resiliency is measured as a function of cost increased due to disturbing events. Thus, three values of cost, resiliency and sustainability are returned to the genetic model to generate new generations. The iteration will continue until none of the three values will improve without degrading any of the other two. Thus, the best solutions are finally obtained through a process called a Pareto optimal front of solutions. It is responsibility of planners to identify the final investment that minimizes cost while maximizing sustainability and resiliency. The final solution depends on the weights given by the planners to the three objectives.

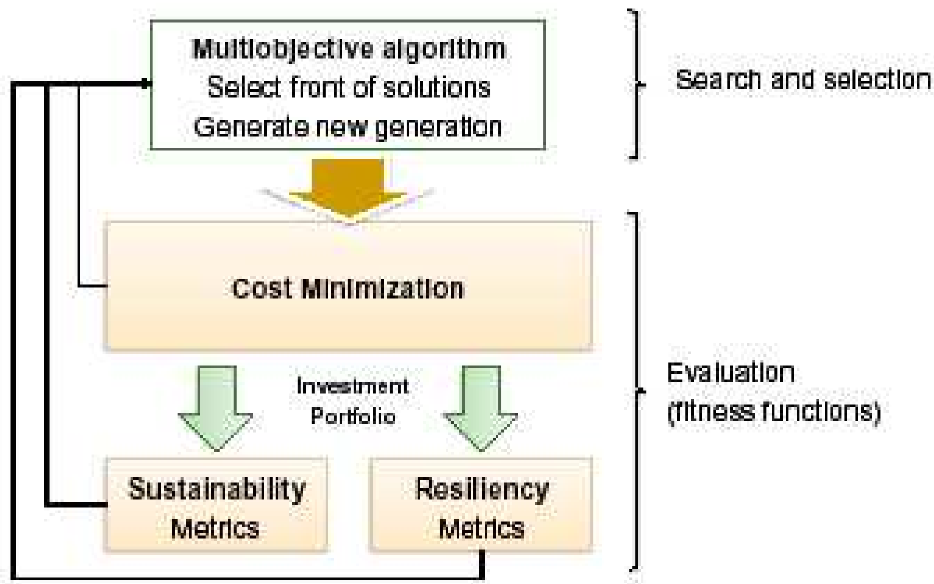

Figure 2-4. NETPLAN multi-objective approach [2]

The genetic algorithm used in NETPLAN is NSGA-II algorithm[17]. “The features that make NSGA-II different from other evolution algorithms include a fast sorting procedure, an elitist approach, a lack of parameters, and diversity preservation.”[2] The sorting and elitist approaches help improve the speed of computation. Lack of parameters allows NSGA-II to be flexibly applied to a variety of problems. Diversity preservation provides uniform solutions along the Pareto front [2]. The computational performance of the NSGA-II algorithm could be further improved by parallelization. A detailed proposal for penalization is describe in reference [2].

CHAPTER 3: MODELCOMPARISON WITH NETPLAN

In this chapter, NEMS and ReEDS are described. Energy and transportation sectors in NEMS and the treatment of intermittent renewable energy are described in detail. Summaries of model comparison among NETPLAN, NEMS, and ReEDS are given. The model comparison provides information for further improvement of NETPLAN. The advantages and disadvantages of NETPLAN, NEMS, and ReEDS based on the model comparison are given.

3.1 NEMS

NEMS was developed by the U.S. Department of Energy (DOE). The purpose of NEMS is to study the interaction of energy system, macro economy, and environment under a wide variety of assumptions and energy policies. Because of its capability for representing the complex interactions of the U.S. energy system, NEMS can be used to project energy, economic, environmental, and security impacts on the United States and to examine the impact of new energy programs and policies[5].

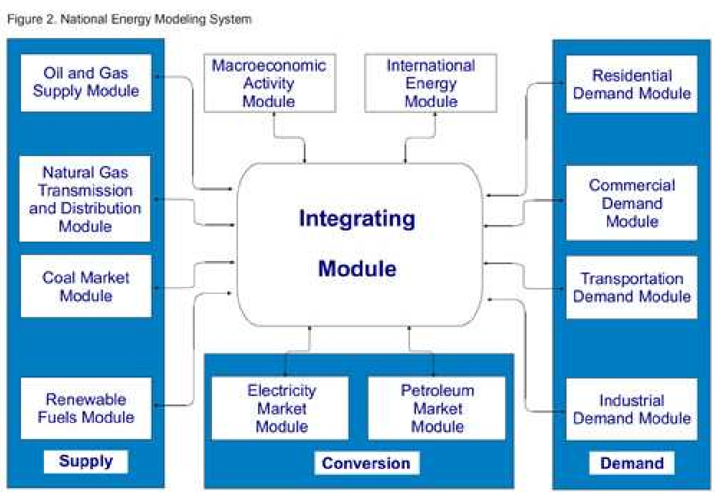

Figure 3-1. NEMS model structure [5]

NEMS is an energy economic model that stresses interaction between macroeconomic and energy sectors. Among energy sectors, two other interactions are represented. The first interaction is between energy supply and demand. In NEMS, the Supply Module, the Conversion Module, and the Demand Module are used to simulate market behavior of producers and consumers in the various energy sectors. The second type of interaction is between the domestic energy market and the international energy market. Data are shared among the four modules (macroeconomic, international market, Demand, supply). The Integrating Module serves as a data management center used to transfer data among the four modules and provide a final solution.

NEMS is an equilibrium model, in contrast to the optimal model. On one hand, the solutions of the NEMS model are obtained when energy demand equals energy supply, while an optimal model seeks to find globally-minimum values subject to a series of constraints. On the other hand, from an economic point of view NEMS is also an equilibrium model, in contrast to a partial equilibrium model[1]. In NEMS, all energy markets (Electrical, Natural Gas, and Oil) reach a supply-and-demand, while a partial equilibrium model (like MARKAL) only considers the balance in one energy market and assumes that prices of other kinds of energy constant.

Although energy markets in NEMS as a whole need to reach an equilibrium situation, some energy aspects can adopt an optimal method to meet their specific objectives. For

[1] **General equilibrium theory** [18] is a branch of theoretical economics. It seeks to explain the behavior of supply, demand, and prices in a whole economy with several or many interacting markets, by seeking to prove that a set of prices exists that will result in an overall equilibrium, hence general equilibrium, in contrast to partial equilibrium. In **partial equilibrium** analysis, the determination of the price of a good is simplified by just looking at the price of one goods, and assuming that the prices of all other goods remain constant.

example, the Electrical Market Module applies the Capacity Expansion Planning (Resource planning) Model to decide how to meet electrical demand at minimum cost; the Coal Distribution Sub-module uses a Linear Programming approach to minimize delivered costs; the Petroleum Market Model uses Linear Programming to maximize revenues minus costs to meet petroleum product demands[5].

3.1.1 Energy Sectors in NEMS

3.1.1.1 Electricity Market Module

The Electricity Market Module (EMM) is included in the energy conversion module that represents the generation, transmission, and pricing of electricity subject to electricity demand, fuel price, technology availability, environmental constraints, and financing [5]. It consists of electrical demand, Electricity Capacity Planning (ECP), Electricity Fuel Dispatch (EFD), and Electricity Finance and Pricing (EFP) sub modules.

The functions of sub modules in EMM and their relationship with other NEMS modules are as follows: the electricity demand module generates the load-duration curve and peak load based on the total annual electricity demand sent from the Demand Module. The LDC, peak load and the fuel price then used by the Electricity Capacity Planning (ECP) sub-module to obtain the generation expansion investment by solving a linear minimum cost problem. Electricity Fuel Dispatch (EFD) determines how to meet electrical demand with minimum production cost based on the current and generation addition obtained from the ECP. Electricity Finance and Pricing (EFP) calculates electricity price using production costs from EFD. EMM outputs electricity price to the demand module, fuel consumption to the fuel supply modules, emissions to the integrating module, and capital requirements to the macroeconomic module.

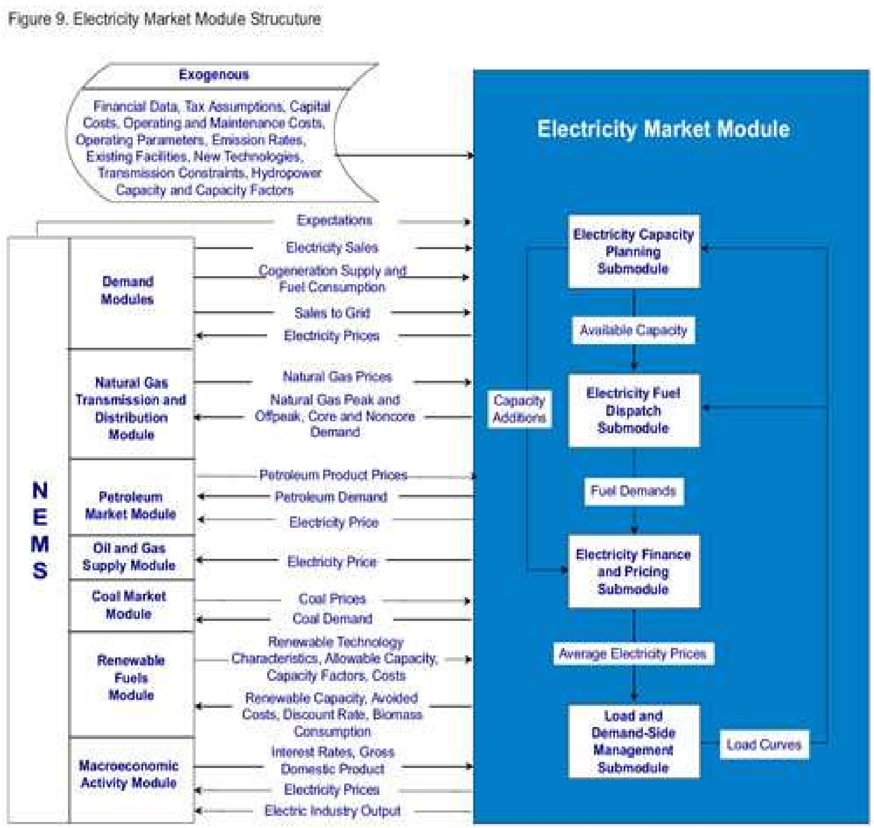

Figure 3-2.Electricity Market Module [5]

Electricity Capacity Planning (ECP) in EMM is quite similar to resource planning in NETPALN. ECP applies an LP method to obtain generation resource addition solutions. The objective function minimizes total investment cost and operation costs. The minimum cost problem is subject to the following constraints:

-Fuel (coal, natural gas and petroleum) supply constraints

-Electricity demand constraints (LDC)

-Peak load reserve margin constraints

-Operational constraints (Must-run, Maintenance, variability of intermittent resources)

-Transmission constraints between regions

-Environmental constraints (SO_2, NO_X, Hg and CO_2)

-Renewable Portfolio Standard constraints

The detailed mathematical formulation of ECP will not be described here due to its large number of variables and constraints. They may be found in reference [19]. However, some features of ECP can be described as follows:

1. ECP utilizes coal production and transportation costs generated from the Coal Market Module (CMM).
2. Existing supply contracts between coal producers and electricity generators are incorporated in the CMM as minimum flows for supply curves to coal demand regions. Dual-level transportation cost is added when the coal demand exceeds existing minimum flows.
3. Natural gas peak load is considered.
4. Co-fire, one being biomass and coal, the other oil and gas, is considered
5. Characteristics of renewable resources are obtained from Renewable Modules that provide ECP with investment cost, renewable resources.
6. All available renewable capacity except biomass is assumed to be dispatched first by the EMM because most renewable sources produce little or no air pollution,
7. Emission control equipment such as FGD and SCR are modeled, but CCS is not included.
8. Earlier retirement for coal is modeled.

9. Distributed generation technologies - base load and peak resources - are considered.
10. A demand storage technology is used to represent load-shifting during the peak load period.

3.1.1.2 Coal Market Module

The Coal Market Module (CMM) represents the mining, transportation, and pricing of coal. It includes a Coal Production Sub-module (CPS) and a Coal Distribution Sub-module (CDS)[20].

The Coal Production Sub-module (CPS) provides coal supply curves for the Coal Distribution Sub-module (CDS) to satisfy coal demands. The supply curves comprise quantity and price pairs. The prices are converted from regression models that measure the mine mouth prices as the function of productive capacity, capacity utilization, productivity, and various factor input costs. In CPS, coal-supply curves are identified by region, coal type, heat content, sulfur content, and mining method (underground or surface). There are a total of 40 coal supply curves generated by CPS and they are shared with the Electrical Market Module (EMM).

The Coal Distribution Sub-module (CDS) sets up the LP model to meet coal demand at the minimum delivery cost subject to environmental, technical, and service/reliability constraints. "CDS receives mine mouth prices produced by the CPS, coal demand from other NEMS components, and provides delivered coal prices and quantities to the NEMS economic sectors and regions" [20].

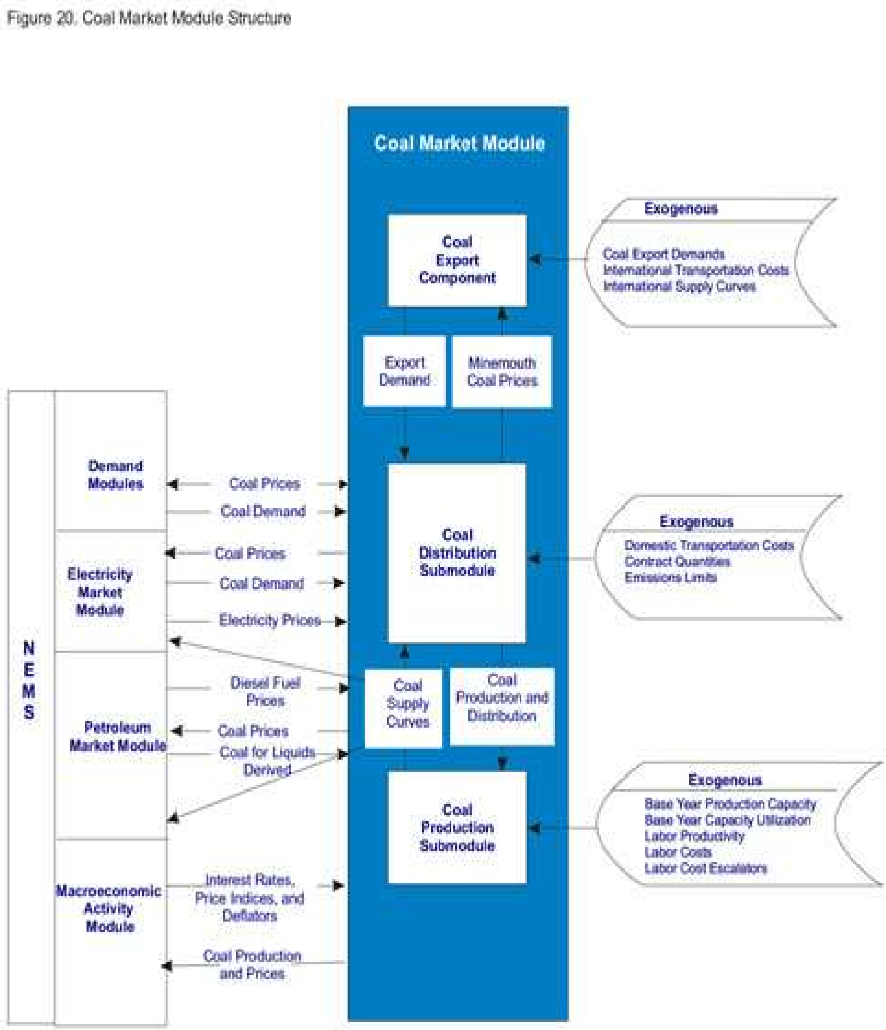

Figure 3-3.Coal Market Module [5]

The CDS communicates with both the Electricity Capacity Planning Module (ECP) and the Electricity Fuel Dispatch (EFD) Sub-module in EMM. The CDS provides detailed input information to the EMM, including coal-supply curves, transportation rates, coal-diversity information (sub-bituminous and lignite coal constraints) and existing supply contracts between coal producers and electricity generators. Existing supply contracts are modeled as minimum flows for supply curves to coal demand regions. This is done for the purpose of reducing computation time, since there are thousands of feasible transport routes for use. Coal demand might increase the existing coal contract for a certain coal supply curve, or a power plant may use a new and previously unused type of coal. In the above cases, an increased transportation rate, called a second-tier rate, will be added[20].

Some features of CMM are described as follows:

1. Includes 40 coal supply curves (price/quantity pairs) incorporating 12 coal types and 14 U.S. coal supply regions.
2. Represents 16 coal-demand regions. Coal demand comes from Residential, Commercial, Industrial, and electrical power components of NEMS and international market.
3. CDS currently contains no descriptive detail on coal transportation by different modes and routes. Only railroad coal transportation is modeled.
4. Only railroad investment in the west is considered.

3.1.1.3 Natural Gas Transmission and Distribution Module

The Natural Gas Transmission and Distribution Module (NGTDM) represents U.S. domestic natural-gas transmission, distribution, and pricing of natural gas127. It includes the Pipeline Tariff Sub-module (PTS), the Distributor Tariff Sub-module (DTS), and the Interstate Transmission Sub-module (ITS).

The Pipeline Tariff Sub-module (PTS) provides tariff curves for the Interstate Transmission Sub-module (ITS), given the previous year's investment in pipeline and storage. Each year, PTS receives pipeline and storage capacity utilization and expansion from other modules in NEMS and updates the transmission tariff using a general accounting framework.

The distributor tariff Sub-module (DTS) sets distributor markups charged by local distribution companies for the distribution of natural gas from the city gate to the end user

[21]. Since the electricity sector does not purchase their gas through local distribution, their "distribution tariff" represents the difference between the average price paid by local distribution companies at the city gate and the average price paid by electric-generator customers. "The difference is a function of natural gas consumption by the sector relative to that consumed by the other sectors. Therefore, the greater the electric consumption share, the greater the price difference between the electric sector and the average 127."

The interstate transmission Sub-module (ITS) is the main integrating module of NGTDM. It is designed to simulate natural gas price. ITS determines the flow of natural gas and the regional market clearing prices between suppliers and end-users, based on end-use demand for natural gas, the production of domestic natural gas, and the availability of natural gas traded on the international market. ITS also simulates the decision–making process for expanding pipeline and/or seasonal storage capacity in the U.S. gas market, determining the amount of pipe line and storage capacity to be added between or within regions in NGTDM.

Main features of NGTDM are described as follows:

1. Determines the investment of pipeline and storage and captures economic tradeoffs between pipeline and storage capacity additions.
2. Represents transmission and distribution service pricing based on pipeline capacity constraints.
3. Uses a two-season model to represent important features of the natural gas market. Since the Electricity Market Module has a seasonal component, peak and off-peak prices for natural gas are provided to electric units.

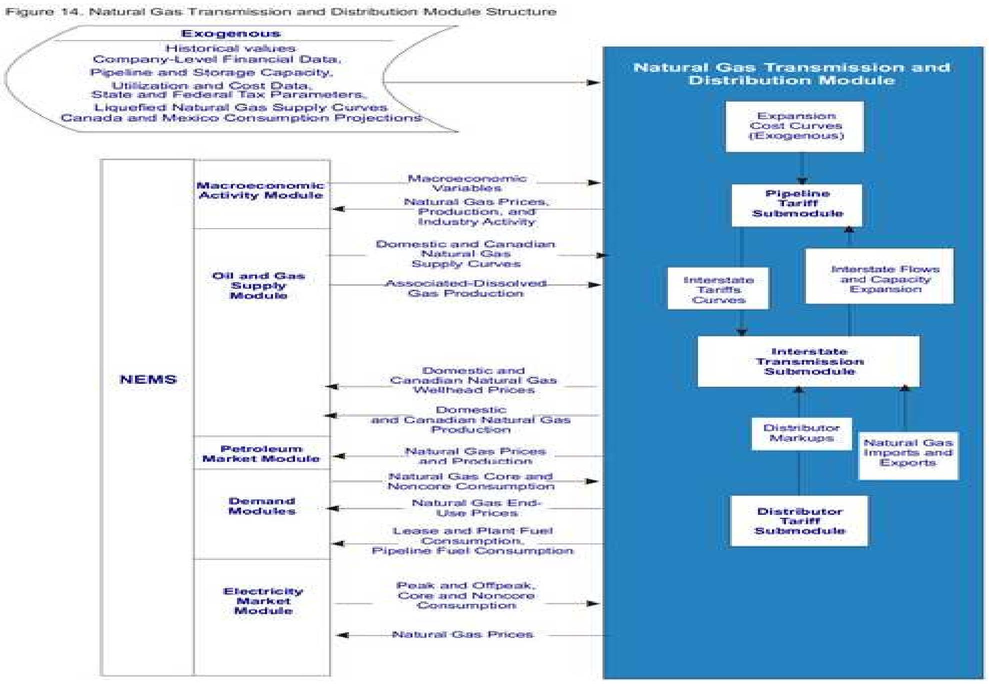

Figure 3-4. Nature Gas Transmission and Distribution Module[5]

3.1.1.4 Petroleum Market Module

The Petroleum Market Module (PMM) represents domestic refinery operations and the marketing of liquid fuels to consumption regions. A linear programming model is used to maximize revenues minus costs to meet petroleum product demands[22].

Prices of petroleum product are passed to residential, commercial, industrial, transportation, and electrical market. An Electricity Market Module (EMM) provides electricity prices and petroleum product demand to PMM.

3.1.1.5 Renewable Energy in NEMS

The renewable fuels module (RFM) represents renewable energy resources, including geothermal, wind, solar thermal, solar photovoltaic, landfill gas, biomass, and traditional hydroelectricity[23].

The RFM provides information concerning cost characteristics (installation cost and O&M cost), capacity factor, source sites, and available capacity of renewable energy resources to the Electrical Market Module (EMM).

For Wind and Solar Electric Sub-modules, capacity factors and capacity credits are used to represent the viability of intermittent renewable resources. Different capacity factors are defined for different time periods and geographic regions. Capacity credits are used to evaluate the contribution of wind power capacity to meet system reliability requirements, given the available land area and wind speed.

Biomass fuel prices are represented by the supply curve. The distribution of biomass fuel is not modeled, but fuel distribution cost is included in the biomass fuel prices of the supply curve considering the accessibility of biomass fuel at the generation regions.

3.1.2 Transportation Sector in NEMS

The transportation demand module (TRAN) projects the transportation sector fuel consumption by transportation mode, and includes the use of renewables and alternative fuels[24].

The Fuel Economy Sub-module (FES) projects new light-duty vehicle fuel economy as a function of energy prices and income-related variables. Higher fuel prices lead to higher fuel-efficiency estimates. The Regional Sales Sub-module (RSS) receives vehicle sales, including both car and light truck sales, from the Macroeconomic Activity Module (MAM). The RSS uses historic vehicle sales and population trends to determine regional sales. The regional sales are then passed to the Alternative Fuel Vehicle Sub-module (AFVS) and the Light-duty Vehicle Stock Sub-modules (LDVS). The AFVS uses regional new car and light truck sales from the RSS to project the sales shares of alternative fuel technologies based on relevant vehicle and fuel attributes. New vehicle sales, including those of car, light truck, and alternative fuel vehicles, are introduced into LDVS to specify the inventory from year to year. The Vehicle-Miles Traveled Sub-module (VMTS) projects travel demand for automobiles and light trucks.

Fuel demand is calculated by transportation mode (car, light trucks, LDV commercial, aircraft, ship and rail). Fleet of vehicles, fuel efficiency, and fuel demand are used to translate travel demand into fuel demand for car, light trucks, and LDV commercial. The Air Travel Demand Sub-module estimates the demand for both passenger and freight air travel. The Freight Transport Sub-module translates estimated industrial production into ton-miles traveled for rail and ships and into vehicle miles traveled for trucks.

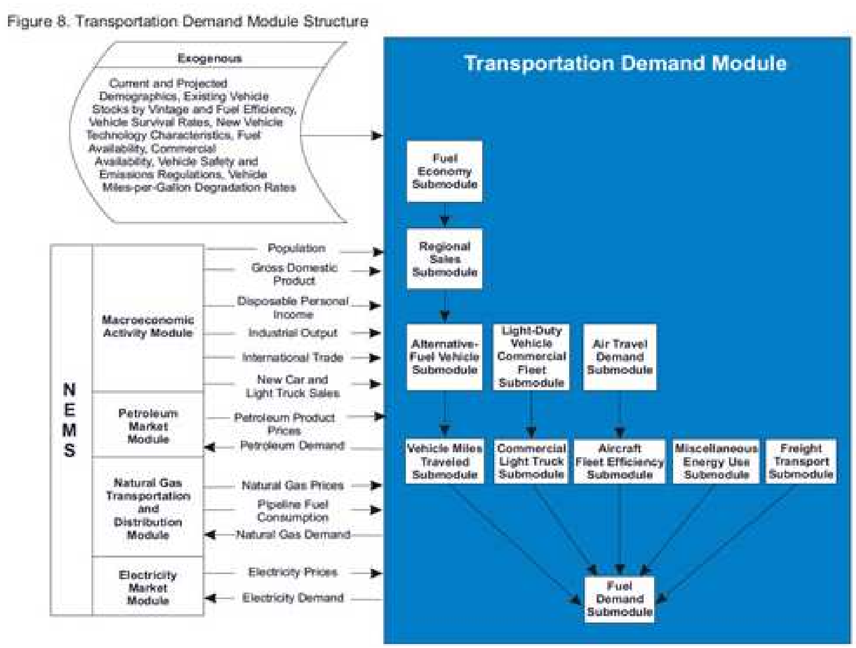

Figure 3-5. Transportation Demand Module [5]

3.1.3 The Algorithm Used to Solve NEMS

NEMS is solved by iteration and may be described as follows: The Integrated Module applies a Gauss-Seidel algorithm to solve a set of nonlinear supply-and-demand equations. Other subsets include supply, demand, and conversion modules that provide the Integrated Module with fuel supply, energy conversion and demand values. For example, the energy demand module generates the energy demand based on energy price, production amount, and economic conditions. The energy supply and conversion module generates the volume of energy supply and energy price based on the demand of the international energy market. Conversion modules provide both the amount and price of electricity and petroleum. For each year, an iteration is run using the Gauss-Seidel algorithm of the Integrated Module. If the energy supply does not equal the energy demand, a step change is made to move the energy supply equal in the direction of the demand. During each iteration, the subsets are solved in sequence using updated values. Iterations will continue until all energy sectors achieve equilibrium and the final solution obtained. Energy prices that make the supply equal to the demand are called the equilibrium prices[25].

3.2 ReEDS

The Regional Energy Deployment System (ReEDS) is a resource and transmission planning model developed by the National Renewable Energy Laboratory (NREL). The main purpose of ReEDS is to optimize investment and operation of power systems in the long term, especially focusing on the investment and operation of renewable energy sources,

ReEDS uses a linear programming optimization model. The objective function is to minimize the investment, transmission, and operating cost of the electrical sector. Its main constraints include load demand constraints, transmission constraints, operating reserve constraints, peak load reserve constrains, renewable portfolio standards, renewable resource limits, and emission constraints. ReEDS stresses the integration of intermittent renewable energy, especially wind energy and has the following features.

1. Different energy conversion technologies are treated separately.

Energy technologies are first divided into categories of renewable energy and conversion energy. Renewable energy is further divided into wind, solar, and non-intermittent energy such as biomass and geothermal. Although both wind and solar energy represent intermittent energy, solar energy is different from wind energy for two reasons. First, solar energy has less variability than wind energy. Second, concentrated solar plants (CSP) generation peaks are coincident with the load, while wind power peaks are not. ReEDS adopts a statistical algorithm to represent the variability of wind output and wind curtailment during off-peak periods.

2. Constraints are modified or added to reflect the integration of renewable technologies.

To represent the characteristics of renewable power technologies and model the impact of integrating intermittent renewable power technologies on the systems operating, ReEDS incorporates capacity installation constraints, transmission constraints, and operational constraints in its mathematic model.

a. Capacity installation constraints

1) **Wind/CSP Resource Constraint:** For every wind class and wind supply region, the total wind/ CSP capacity installed in the region must be less than the total wind/solar resource in that region.

2) **Wind/CSP Growth Constraint:** The total growth in wind /CSP power capacity for each period must be less than some specific fraction of the national wind power capacity (MW) at the start of the period.

3) **Wind/CSP Installation Growth Constraint:** The total growth in wind/CSP capacity in each region for each period must be less than some specific fraction of the regional wind capacity (MW) at the start of the period.

4) **State /national Renewable portfolio standard (RPS) Requirement:** ensures that total annual renewable generation must exceed a specified fraction of the state/national electricity load. Otherwise, a penalty will be paid.

b. Transmission constraints

ReEDS allows either a transmission model or a transportation model to be used to represent transmission constraints. When a transportation model is used, power flows along the corridor are treated as decision variables and solved by the LP method. In this case, link flows are independent from each other, which may result in overestimation of transmission capacity. When a transmission model is used, power flows along corridors must obey Kirchhoff's laws. ReEDS calculates link flow using an exogenous power transfer distribution factor (PTDF) matrix and net injection into each balance area. It also calculates power flow along each corridor resulting from the net contract within each balance area. Both power flow and contract power flow must be within the transmission limits of the corridors.

1) **Power flow transmission constraint:** ensures that power flow along each transmission corridor does not exceed the existing transmission capacity within each time-slice.

2) **Contracted transmission constraint:** Ensures that there is sufficient transmission capacity between two contiguous balancing authorities to transmit renewable and contracted conventional capacity. In ReEDS, capacity contracts are used in planning reserves, so this constraint need not be applied to each time slice.

c. Operating constraints

In ReEDS, spinning reserve[2], quick-start reserve[3], and interrupted load[4]are used for operating reserve. They are treated in detail since the variability characteristics of intermittent renewable energy, especially wind energy, may cause challenges to a system's operating reserve. Since wind forecasting always contains errors, more operating reserve is needed to compensate for them. Additionally, wind generation output is variable, which requires sufficient spinning reserve and limits the amount of quick-start reserve and interrupted load. ReEDS breaks operating constraints into four constraints. Each of these constraints is applied to each time-slice in each reserve-sharing group region.

1) **Operating reserve requirement 1:** Ensures that the spinning reserve, quick-start capacity, and interrupted load are adequate to meet normal operating requirements (7.5% load demand requirement) and additional reserve required by wind forecast errors.

2) **Operating reserve requirement 2**: ensures that conventional and storage technology capacity serving quick-start are less than 6% of load and demand requirements plus 5/6 forecast error reserves.

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[2]. Spinning reserve is the unloaded generation that is synchronized and ready to serve additional demand.

[3]. Quick-start reserve is not connected to the system but is capable of serving demand within 10 minutes.

[4] Interruptible load is the load that can be removed from the system within a specified time

3) **Operating reserve requirement 3**: Requires spinning reserves have to make up at least 1.5% of total demand in a reserve sharing region in all time-slices.

4) **Operating reserve requirement 4**: Defines the forecast error reserve to be equal to the forecast error reserve requirement for existing variable-resource capacity plus forecast error reserve requirement for new variable-resource capacity. The latter is calculated before each iteration and used as an input to the model.

3. Parameters based on a statistical approach are used to represent the variability of intermittent renewable resources.

In ReEDS, the output of individual variable resource renewable energy (VRRE) plants are viewed as random variables and assumed to follow a normal distribution function. However, the model actually uses the output of aggregated VREE plants in a wind-source area. In order to obtain the contribution of all VREE plants to regional demand, a new random variable containing all output of the VREE plants is introduced. The mean value and standard deviation are used to represent this new random variable. The mean value of the new random variable is the sum of the mean values of individual VREE plants. Since the outputs of VRRE plants are correlated with one another, the standard deviation should not be summed. ReEDS calculates the standard deviation of the new random variable through a standard statistical formula using a Pearson correlation matrix[5] [6].

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5. $\sigma_{Rr}^2 = \sum_{k \in R_r} \sum_{l \in R_r} P_{k,l} \cdot \sigma_k \cdot \sigma_l$
Where:

$\sigma_k$and $\sigma_l$are the standard deviation of the particular VRRE site
$P_{k,l}$is the Pearson correlation coefficient
$R_r$isthe set of VRREs contributing to region r.

Based on the mean value and standard deviation of all VRRE plants, capacity value, surplus, and wind curtailment are calculated for each supply and each sink region for each period before the main optimization is performed.

1) **Capacity value**: This is the capacity credit given to the VRRE contribution to meet the reserve margin constraint in each sink region. Capacity values are used in the peak load reserve margin constraints. The peak load reserve margin requirement ensures that the conventional generation, stored power capacity, and wind power capacity and concentrated solar power plant generation during the peak summer period is large enough to meet the peak load plus a reserve margin.

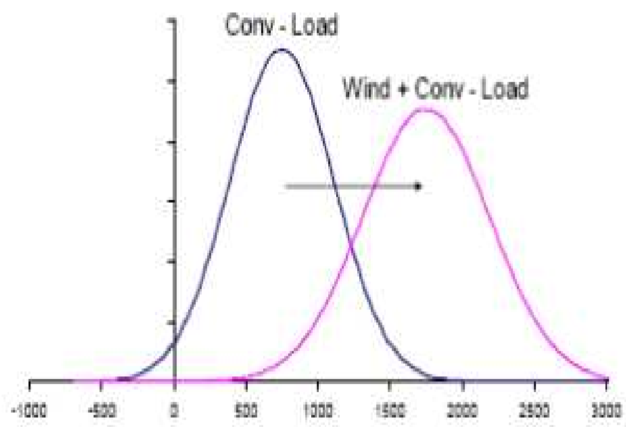

Figure 3-6. Wind capacity value [26]

In Figure 3-6 load (L), conversional generation availability (C), and wind availability (W) are viewed as random variables. A random variable U=C+W-L is constructed. Since conventional generation availability (C), wind availability (W) and load (L) are independent of one another, the mean value of X is the sum of the mean values of C, W, and L. The standard deviation of X is

$$\sigma_U = \sqrt{\sigma_C^2 + \sigma_W^2 + \sigma_L^2}.$$

Wind availability with effective load carrying capacity (ELCC) could be substituted, defining the amount of electrical demand that may be added in each time-slice for an incremental increase in capacity of a given VRRE technology without increasing the loss of load probability. Assuming random variable $V = C - (L - \Delta L)$, where ΔL is the wind ELCC, has the same distribution function as a random variable, then U can be estimated by equating the loss of load probabilities (LOLP) of random variable U and V:

$$P(U < 0) = P(V < 0)$$

The capacity value is then obtained by defining the wind capacity value as$\Delta L/TR_x$, where TR_x is the total wind installation capacity. Similarly, the marginal capacity value associated with the added VRRE capacity is calculated for each region and wind class. Marginal capacity values are calculated before each optimization and used as input parameters.

2) **Surplus and wind curtailments**: The surplus of VRRE generation is calculated when the VRRE generation exceeds what is needed in the system during off-peak periods. There is no solar curtailment because CSP is less variable than wind generation and CSP peaks are coincident with load peaks.

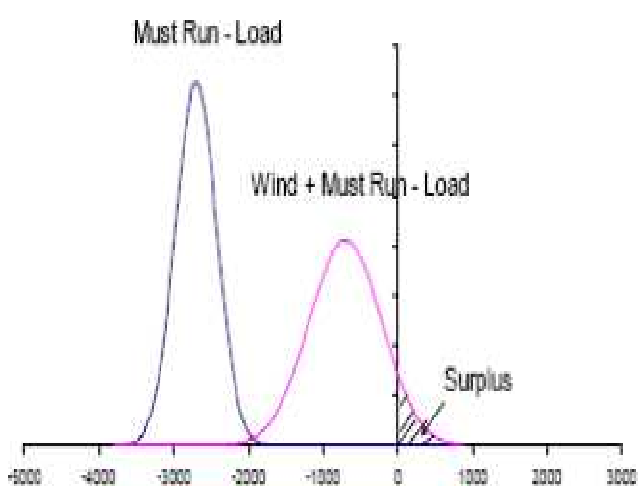

Figure 3-7. Wind curtailments [26]

To calculate the wind power surplus, random variable Y=M-L+R is defined, where M is must-run generation, L is load, and R is wind power availability. Wind curtailment is calculated using:

$$u_s = \int_{-\infty}^{0} sf(s)ds + \int_{0}^{\infty} sf(s)ds$$

By asserting that if Y<0, S=0; if Y>0, S=Y, then

$$u_s = 0 + \int_{0}^{\infty} yf(y)dy$$

Wind power curtailment is estimated based on base curtailment for current VRRE resources plus additional curtailment from new VRRE resources, adjusted by current and new must-run generation and storage capacity. Wind power curtailment is used in load-demand constraints and renewable portfolio standards constraints as a negative part of the VRRE generation.

4. Storage and demand-side technologies

Storage is used withinthe main constraints, including load-demand constraints, peak-load reserve constraints, operating-reserve constraints, and wind-curtailment constraints. Since ReEDS uses time-slices based on LDC, storage is not modeled across time to directly operate with intermittent resources.

ReDES involves demand-side technologies, including interrupted load, thermal-energy storage in buildings, and plug-in electric and hybrid vehicles. They are used as operating reserves to adjust demand.

5. Five types of regions are used in the ReEDS model

To better represent the renewable resources, 356 supply/demand areas for renewable energy were created specifically in the ReEDS model. Using 356 renewable-energy supply/demand regions, an electrical load based on county population can be determined;

State-level RPS can be modeled; distance between the renewable supply and demand could be estimated. Besides the supply/demand areas, 3 interconnect regions, 32 RTO regions, and 134 balance areas are used to reflect operational practices and reliability requirements in bulk power systems.

3 interconnect regions - electrically asynchronous regions, isolated from oneanother except for a limited number of AC/DC/AC connections.

13 NERC regions - 13 NERC regions are used so that results can be compared with results from other models also using NERC regions.

32 RTO regions - 32 regional transmission organizations, each of which contains one or more balancing authorities. Reserve-margin requirements, operating-reserve requirements, and wind curtailments are monitored at the RTO level.

134balance authorities - power balance on wind and CSP Energy is enforced within each balancing authority.

6. Use recursive optimization process

ReEDS solves an LP for each of the 23 two-year time periods as it moves successively from 2006 to 2050. Resource expansion and dispatch are made sequentially for every two-year period[6]. The objective function in ReEDS includes net present value (NPV) for new investment in two years and 20 year NPV operating cost for all capacity. A two year basis LP model contains more load demand segments and more detailed operating constraints for intermittent renewable-energy operation. This methodology has several advantages:

1) Allows for use of model updating parameters calculated outside the LP model. These parameters are PTDF matrix, capacity value, VRRE forecast error, and wind curtailment.

2) Allows ReEDS to simulate the dynamic interaction between fuel supply and electrical demand, as long as a fuel supply curve and electricity demand elasticity are provided.
3) Yearly revenue of power plant can be obtained for each period. As a result, the retirement decision for a power plant can be determined by calculating whether the revenue of the power plant exceeds the total cost.
4) LMP could be obtained from a two year basis period LP model.

The disadvantage of a two year basis is that the investment decision making is not based on minimizing 40 year total cost.

3.3 Comparison of NETPLAN, NEMS and ReEDS

Table 3-1 to Table 3-12 are the model comparison of three models.

Table 3-1. Model comparison overview

Time horizon			
	NETPLAN	NEMS	ReEDS
	Long term planning for 40 years	Midterm planning for 25 years	Long term planning for 40 years
Region definition			
	NETPLAN	NEMS	ReEDS
	13 NERC regions Node-arc structure	13 NERC regions 14 Coal/biomass demand and supply regions 16 NG regions	3 interconnect regions 13 NERC regions 32 RTO regions 134 balance authorities 356 renewable supply and demand areas

Table 3-2. Model comparison on raw fuel resources

	NETPLAN	NEMS	ReEDS
Coal	Coal supply is specified by type and location and is connected to a fictitious source node.	1.Coal Market Module (CMM) provides 40 coal supply curves by coal type and region, shared with Electrical Market Module (EMM) 2. Coal supply curves are updated for each year in the projection period.	N/A
Oil and Gas	Oil and gas supply is specified by the location and connected to a fictitious source node.	NG Transmission and Distribution Module (NGTDM) provides supply curves for the annual production and distribution costs.	N/A
Renewable Energy	Wind and solar resources are characterized by capacity factor for each region. Geothermal resources are limited by location and maximum investment capacity. No Biomass resource supply.	Renewable fuel module (RFM) generates the following data to ECP Sub-module in EMM module. Wind: The availability of wind resources, capacity factor, capacity credit, the cost and performance of wind turbine generators. Solar: Represents both photovoltaic and concentrating solar power installations. Provides the EMM with time-of-day and seasonal solar availability data for each region, as well as current costs. Biomass Provides the EMM with supply curves for biomass fuel. Geothermal: Provides the EMM with supply (megawatts) of new geothermal generating capacity and its related average cost and performance characteristics	Wind Wind resource is divided by 5 classes and 3 types (onshore, shallow offshore, and deep offshore).Wind supply curves are available for each wind class, each type of wind resources and each region Solar Solar resource is also divided into five classes. Solar supply curves are available for each solar class, and each region

Table 3-3. Model comparison on energy related transportation

	NETPLAN	NEMS	ReEDS
Coal	1. Currently transported by rail road. 2. History contracts are not used. 3. Total transportation cost is calculated by per mile transportation cost multiplied by distance.	1. Currently transported by rail road. ECP utilizes production and transportation costs generated from CMM. 2. Existing supply contracts between coal producers and electricity generators are incorporated in the CMM as minimum flows for supply curves to coal demand regions. 3. Transportation routes are treated as exogenous input. Two tiers coal transportation cost are used when the current transportation is greater than the contract transportation. 4. Transportation rates are modified over time due to the changing productivity and equipment costs.	N/A
Nature gas	1. Nodes and arcs structure are used to represents pipeline and storage infrastructure in the LP model. 2. Operation costs for pipeline and storage are assigned as input parameters. 3. Pipeline and storage investment are treated as decision variables.	1. Nodes and arcs are used to simulate the interregional flow and pricing of gas 2. NG transmission and Distribution Module (NGTDM) provides distribution costs. 3. No optimal model is used to determine the investment.	N/A
Biomass	Currently not modeled.	1. RFM assumes a fixed transportation distance in calculating the biomass transportation costs. 2. No transportation route is specified.	N/A

Table 3-4. Model comparison on non-energy related transportation

Non energy related transportation			
	NETPLAN	NEMS	ReEDS
	1. State to state transportation is represented. 2. Arc and node structure is used. 3. Non energy commodity transportation demand is defined on arc and is treated as exogenous input. 4. Transportation routes are determined. Transportation mode and fleets could be chosen. 5. Vehicle and infrastructure investment are treated as decision variables.	Transportation Sub-module in the demand module do the following things: 1. Energy or fuel demand by transportation system is estimated. 2. Plug-in hybrid electric is forecasted; the corresponding electricity demand is calculated. 3. Miles travel is estimated. Transportation Sub-module does not do the following things: 1. No arc and node structure is represented. 2. No infrastructure investment is made. 3. No transportation capacity constraints are considered.	N/A

Table 3-5. Model comparison on capacity attributes

	NETPLAN	NEMS	ReEDS
Capacity Types	-natural gas combustion turbine combined cycle NGCC combined cycle with carbon capture and sequestration (CCS) -coal pulverized coal, integrated gasification combined cycle (IGCC) -nuclear - Hydro -wind Inland offshore -solar - biomass -geothermal -oil -fuel cell -landfill gas/municipal solid waste -others	Existing Coal Steam New Scrubbed Coal Advanced Coal Advanced Coal with Sequestration Gas/Oil Steam Turbine Existing Combustion Turbine New Conventional Combustion Turbine New Advanced Combustion Turbine Existing Gas/Oil Combined Cycle New Conventional Gas/Oil Combined Cycle New Advanced Gas/Oil Combined Cycle New Advanced Combined Cycle with Sequestration Fuel Cells Conventional Nuclear Advanced Nuclear Biomass (Wood) Municipal Solid Waste Geothermal Hydroelectric Pumped Storage Demand Storage Wind Solar Thermal Solar Photovoltaic Distributed Generation - Base load Distributed Generation - Peak load	-natural gas combustion turbine combined cycle combined cycle with carbon capture and sequestration (CCS) -coal traditional pulverized coal, unscrubbed, scrubbed, or cofiring modern pulverized, with or without cofiring integrated gasification combined cycle (IGCC) with or without CCS -oil gas steam -nuclear -wind Inland offshore -solar -dedicated biomass -geothermal -landfill gas/municipal solid waste -others (distributed PV)
Storage	--	1. Pumped storage 2. Demand storage technology through smart meter is used to simulate the load shift and offset the peak demand.	Pumped hydropower (PHS) batteries compressed air energy storage (CAES) ice storage

Table 3-6. Model comparison on capacity attributes (Continued)

Distributed generation	N/A	1.Distributed generation options are represented as generic technologies serving peak and base loads 2. Distributed generation could reduce the need for investment in new transmission and distribution (T&D) equipment.	N/A
cogenerations	N/A	cogenerations is determined by the end-use demand modules	N/A
Retirement treatment	1. Obtain announced capacity retirements from exogenous inputs 2. Is able to determined earlier retirement due to the installation of FGD.	1 Obtain announced capacity retirements from exogenous inputs 2 ECP also evaluates retirement decisions for fossil and nuclear plant if appropriate.	Obtain announced capacity retirements from exogenous inputs
Retrofit treatment	Retrofitting existing coal-fired plants with emission control equipment.	Retrofitting existing coal-fired plants with carbon capture and sequestration (CCS) equipment, SO2, NOX, and mercury.	Coal plants have the option of being retrofitted with a scrubber and CCS.
Emission allowance	N/A	Cost of Purchasing emission allowances is considered when decide build a new capacity type.	N/A

Table 3-7. Model comparison on operation issues

	NETPLAN	NEMS	ReEDS
Must run	Must run capacity could be considered.	Must run capacity is considered.	Must run capacity is considered.
Reserve margins	Peak load reserve margin.	In regulating market, reserve margins are derived from the NERC requirement. In deregulating market, optimal reserve margin is calculated.	1. Additional operating reserve is required by variable resource renewable energy (VRRE). 2. Operating reserve is divided by spinning reserve and quick start capacity.
Intermittent resource capacity credit	Capacity credit for each intermittent resource and each region is evaluated separately.	1. Capacity credit is determined as a function of the estimated average contribution that all units of that type (wind or solar) will provide to meeting an assumed system reliability goal of 99.999% availability. 2. Capacity credit for each intermittent resource is evaluated separately.	1. Capacity credit is calculated with the mean and standard deviation of all VRRE plants contributing to a sink region. 2. Capacity credit is calculated in each supply and sink region for each period
Wind curtail	N/A	N/A	Wind curtail is calculated based on the historic statistic data.
Fuel switch	Fuel switch could be made among four types of coal supply to reduce the SO2 emission.	For coal units, considers fuel switching as one of the options to reducing emission. For dual-fired units, considers switching between alternate fuels such as oil and natural gas. For non-coal dispatchable technologies, considers fuel switching between the available fuel types.	Coal plants have the option of purchasing low-sulfur coal
Co-fire	N/A	Consider coal capacity types to co-fire with biomass	Consider coal capacity types to co-fire with biomass.
Electricity trade	Interregional trade	Interregional trade.	Interregional trade, import and export among balance areas.

Table 3-8. Model comparison on Transmission lines

Transmission lines			
	NETPLAN	NEMS	ReEDS
Transmission lines structure	Transmission lines could be modeled in detail using node and arc structure.	Interregional transmission lines are represented.	Existing and new transmission lines are modeled
DC power flow	Power flow along the transmission could be calculated using DC power flow equation.	N/A	PTDF is used to determine the power flow along the transmission lines.
Transmission costs	Use average transmission costs	Use average transmission costs	Use average transmission costs
transmission losses	Transmission losses can be modeled by a piecewise linear concave function where the slopes decrease with the flow.	Transmission losses are modeled by some fixed percentage of total energy transmitted.	Transmission losses are modeled by some fixed percentage of total energy transmitted.
Transmission technology	HVAC EHVAC HVDC Underground Superconducting Pipe Regional Transmission: HSIL, GIL, HVDC**Error! Reference source not found.**[27]	N/A	N/A

Table 3-9. Model comparison on investment issues

Investment issues			
	NETPLAN	NEMS	ReEDS
Market sharing algorithm		Allow investing competitive but not least cost alternatives.	
Capital costs	Capital costs could be variable with time.	Capital costs are variable because learning factor represents reductions in capital costs due to "learning-by-doing".	Capital costs could be variable with time.

Table 3-10. Model comparison on constraints

	Description of constraints	NETPLAN	NEMS	ReEDS
Fuel Supply Const.	Coal: Coal production by a particular supply curve must satisfy the coal transported to coal plants. Nature gas: The production of NG must satisfy the transportation requirement for nature gas-fired generation.	√	√	
Fuel Demand Const.	Coal: Coal transported from the coal supply regions must satisfy the fuel consumption for each coal cap type. Nature gas: The transportation of NG must satisfy the NG consumption for nature gas-fired generation.	√	√	
NG Seasonal Const.	Nature gas: Ensure the sufficient quantities of NG are delivered to each fuel region in both peak and off-peak periods.	√	√	
Constraints on wind/CSP resource	Wind/CSP resource constraint: The sum of all wind capacity installed must be less than he total wind resource for each region. Wind/CSP supply curve: (different cost)		√	√
Emission	SO2 emission restricted by current regulation NOx emission restricted by current regulation Hg emission restricted by current regulation CO2 emission regulation	√	√	
Generation demand requirement	The total power (capacity within the region plus imported power) available satisfy the load for each region in each time period	√		√
Load demand requirement	For each load segment, require that sufficient capacity is allocated to meet corresponding capacity requirement. [This constraint is the alternative for generation requirement]		√	
Renewable portfolio const.	The total annual renewable generation/capacity must exceed a specified fraction of the state electricity load.		√	√
Reserve Margin Requirement	Ensures that conventional, renewable and storage capacity available during the peak load period meet the requirement of peak load plus a reserve margin.	√	√	√
Operating Reserve Requirement	Ensures that the spinning reserve, quick start capacity and storage capacity meets the normal operating reserve requirement and additional operation reserve imposed by wind.			√
Spinning Reserve Const.	Ensures that the generation of conventional plants comprises at least a minimum fraction of the total generation in each time slice for each region.			√

Table 3-11. Model comparison on constraints (Continued)

Must run const.	Specify the minimum generation requirement based on historical utilization rates for must run capacity.		√	√
Capacity Dispatch Const.	Ensures the dispatchable capacity de-rated by the average forced outage rate and planned maintenance satisfies the requirement for load, quick start and spinning reserved.			√
Planned maintenance Const.	Ensure the total of the seasonal planned maintenance scheduled for each dispatchable technology satisfies the annual maintenance requirement.		√	
Transmission Const.	Limits the total amount of the power that can be transported. Contracted Transmission constraints (ReEDS)	√	√	√
Storage requirement	1.Storage requirement The generation the storage provides must be replaced in other time periods (mainly for demand storage technology). 2.Energy balance Energy discharged from storage type must not exceed the energy used to charge storage. 3. Storage dispatch const. Ensures that storage capacity is adequate to supply all charging power, discharging power and operating reserve demand.		√ (1)	√ (2 / 3)
Capacity build limits	Wind/CSP growth constraint: New capacity must less than a fraction of national or regional wind capacity at the start of the period. (ReEDS) Distributed generation build limit (NEMS)	√	√	√
Storage build limits	Limit the storage capacity		√	√
Transmission line build limits	Limit the power that can be transmitted.	√	√	√

Table 3-122.Solve approach

	NETPLAN	NEMS	ReEDS
	40 year LP, GA	Gauss-Seidel, LP in EMM	2-year basis LP
Benefits			
	Co-optimize power systems and fuel supply systems. Make trade off among multi-objectives. Minimize overall 40 year total cost.	Is able to get equilibrium fuel demand/supply and fuel price. Parameters in resource planning model could be updated. Yearly production cost and LMP could be calculated	Time temporal slices and detail constraints could be added by reducing the model scale. Parameters which are calculated outside LP could be updated. 2 year LMP is calculated.
Weaknesses			
	Require large computation time	Require large computation time. Gauss-Seidel method has potential problem of no convergence.	Planning results is not based on minimize overall 40 total cost.

3.4 Strengths and weaknesses of NETPLAN, NEMS, and ReEDS

Based on the model description and comparisons, strengths and weakness of NETPLAN, NEMS, and ReEDS are summarized below:

Strengths of NETPLAN:

1. NETPLAN is an integrated planning model that includes both energy-system planning and transportation-system planning.

In NETPLAN, the energy system is defined as a combination of electrical and associated fuel systems (coal, natural gas, oil), with the electrical system highly related to both the fuel system and the transportation system. A fuel supply such as coal, natural gas, oil, or biomass, and needed for operation of electric power plants, must be transported through some combination of railroad, fuel pipelines, highways and rivers. The investment in the electrical system requires a corresponding investment in the transportation system. The integrated-planning model avoids transportation limits on fuel supplied to the electric system and guarantees overall cost optimization in two capital intensive industry systems.

Since electrical and transportation systems account for most harmful emissions[27], another benefit of combining electrical and transportation systems is that emission constraints can be included in analysis.

With the large potential development of electrical vehicles, electrical systems and transportations system are even more closely connected. In the NETPLAN model the presence of electrical vehicles in the transportation system as well as the interaction between transportation and electrical systems due to electrical vehicles can be modeled and analyzed.

In the other two models mentions, NEMS has vehicle forecast but no transportation system planning, and ReEDS does not have multi-sector design.

2. NETPLAN is a multi-objective rather than a single objective model.

NETPLAN performs resource planning not only based on minimizing total cost but also based on maximizing the system's resilience and sustainability. NETPLAN defines resilience as the ability to minimize and recover from consequences of an event for an anticipated state of the system[11].In NETPLAN, sustainability means minimizing costs, emissions, new land usage, water usage, and consumption of natural resources[13].In contrast, electric resource planning models in both NEMS and ReEDS use a single-objective approach. However, cost minimization alone cannot embrace the overall planning criteria

[28], and a planning model that minimizes cost while at the same time maximizing resilience and sustainability is more adaptive to meet the planning criteria.

A multi-objective model generates a number of “good” solutions, called the Pareto optimization frontier, instead of a single “best” solution. These solutions provide options for the planner to make a trade off among cost, resilience and sustainability.

3 NETPLAN uses a network flow LP model instead of a general LP model

NETPLAN applies this network flow LP model to set up its cost-minimization model. One of the important features of the network flow LP model is that it uses arcs and nodes to represent system elements.

a. The electrical system, the fuel system (coal, natural gas, and oil), and the transportation system can be represented in one model.

The network flow LP model enables NETPLAN to model the electrical system, fuel system, and transportation system in one planning model. ReEDS does not contain multi sectors. Although NEMS includes the fuel system and transportation system, NEMS stresses the interaction among the energy markets. Therefore, the Electrical Market Module, the Coal Market Module, and the natural gas transportation and distribution modules are separated. An integrated process is performed to run these modules in sequence to obtain the final solution.

b. Transmission planning and resource planning could be integrated in one model.

The arcs and nodes structure in NETPLAN facilitates the representation of transmission lines. It allows adding DC power flow and transmission limitations in the model so that transmission congestion can be considered. Transmission line investment can be considered to relieve congestion so long as it can reduce total investment and operational cost. By adding both investment and operational cost of transmission lines into the objective function and adding DC power flow and branch flow as constraints, an integrated model with both transmission planning and resource planning could be achieved.

c. More accurate electrical transmission losses can be modeled.

In NETPLAN, electrical transmission losses can be modeled by a piecewise linear concave function in which the slopes decrease with the flow. Although both NEMS and ReEDS represented transmission losses, they are simplified by some fixed percentage of total energy transmitted.

d. The network flow LP method is faster compared to the general LP method. Experience has shown that it is twice as fast[1].

Weaknesses of NETPLAN:

1. NETPLAN requires more forecasting data than other power system planning model.

First, according to EIA 2010 data, electrical systems account for 92.42% of coal consumption, 31.37% of natural gas consumption, and 4.87% of oil consumption [29]. To represent operations and investment in the coal and natural gas infrastructure, energy demand data (especially for natural gas) from other industries is needed. Since NETPLAN does not represent energy demand from these other industries, they are treated as input data.

Second, the transportation system also requires forecasting data. Knowledge of transportation demand over the next 40 years is required. Additionally, there are many choices of transportation routes, transportation modes, and transportation fleets that the model could not fully represent.

2. NETPLAN requires extensive computation.

Electrical resource planning modeling is a problem of significant dimensions. It contains thousands of constraints and addresses a 40-year resource planning interval, while simultaneously considering several time segments within each year. NETPLAN also requires even more computation since it incorporates a transportation system planning model and sets up multi-objective models. Although bender decomposition and parallel computation reduce the time for computation, NETPLAN still needs very long computation time.

Strengths of NEMS:

1. Simulating interaction among energy, economic, and environmental segments.

NEMS is a 3E model that reflects interaction among energy, economic, and environmental segments in one model. Energy sector activity, especially energy price, has significant impact on the macro economy that in turn provides information regarding the GDP, interest rates, income levels, and population to the energy sector. Energy demand is calculated based on economic information, energy efficiency, and geographic features. The energy supply module includes investment planning, production simulation, and energy delivery. Either an econometric method or an optimization method can be used to simulate activities in the energy supply sector. Emission constraints or regulations could be set to reflect impact due to environmental concerns.

2. Simulation of the international energy market and its interaction with the domestic energy system

NEMS simulates the international energy market and its interaction with the domestic energy market. Energy imports and exports both impact the domestic energy supply which in turn impacts the domestic energy price. One example of such impact is that, if US decides to export natural gas to the international market because of an increase of total natural gas supply in US, the natural gas price may still increase due to increase in both international demand and domestic demand.

3. Simulating interactions among energy supply, demand, and price within the US domestic energy system.

NEMS can simulate the dynamic interaction among raw energy supply, energy conversion, and energy demand. Energy price serves as the main indicator for adjusting energy demand and supply to make them attain an equilibrium status. Energy elasticity reflects the change in energy demand in response to a change in energy price. The required fuel supply is determined based on both energy demand and energy price. Since energy demand can allow a choice between different fuel types, such as natural gas and electricity, energy substitution can be simulated.

Weaknesses of NEMS:

1. NEMS is an equilibrium model rather than an optimal model. It cannot choose among alternative policies

NEMS is an equilibrium model and is therefore policy-driven, meaning that the user identifies a load projection along with a policy to be evaluated in terms of use of resources and technologies, costs, energy supplied, and environmental impacts like resulting emissions.

In contrast, an optimization model is policy-driven, i.e., the user identifies a load projection together with available resources and technologies, and then selects the best of them according to some stated objective.

2. NEMS uses a transportation model rather than a transmission model for resource-expansion planning.

Although inter-regional transmission lines are represented in NEMS, resource expansion planning in the EMM module uses a transportation model rather than a transmission model. A transportation model assumes independent energy flow along different paths. In contrast, a transmission model applies DC power flow equations to power flow, meaning that the energy flows along different paths are not independent. The difference between the two models is that the transportation model will tend to overestimate the transmission capabilities of an electric grid.

3. The 25-year time span is not long enough for energy and transportation long-term planning

Both energy and transportation systems are capital-intensive, and once the infrastructure is built it is usually expected to last up to fifty years or more. Therefore, a time span longer than 25 years must be considered to avoid possible financial loss.

Strengths of ReEDS:

1. Stresses the impact of renewable energy on power-system planning

ReEDS aims to incorporate renewable energy to meet electrical demand at minimum cost. Principal renewable technologies include wind, solar, geothermal, and hydroelectric. The model includes available renewable resources by location. Storage and demand response are used as auxiliary methods for meeting both energy and peak load demands. Storage is modeled to reflect wind-surplus saving, resource-firming, and ancillary services. Demand response is modeled to reflect load shifting and interrupted demand.

2. Reflects variability and reliability issues caused by resource intermittency

Intermittent resources, especially wind, have variability that in turn impacts power system operation and reliability. ReEDS considers five resource classes for wind and solar power. Capacity factor adjustments by time-slice were made for each class in each region. Capacity values for intermittent resources are used to satisfy peak-load reserve margin constraints. Capacity values may change from year to year to reflect the impact of concentration of wind resources. Wind curtailment during off-peak periods is calculated and storage during on-peak periods is performed to avoid energy waste.

To reflect the impact of wind resources on power-system operation, ReEDS adjusts the operating reserve margin by adding a wind-forecast error. It also includes constraints to designate the minimum proportion of traditional resources and minimum proportion of spinning reserve used for operating reserves.

3. Detailed representation of power systems network

ReEDS includes 132balance authorities defined by NERC, with transmission lines among all 132 balance areas represented. DC power flow along the transmission lines could be calculated using PTDF, so ReEDS is a transmission model involving transmission constraints in LP. Although transmission upgrading is not currently implemented in ReEDS, the transmission model in the future will enable ReEDS to do both resource and transmission planning.

Weaknesses of ReEDS:

1. ReDES focuses on the power-system sector and does not consider interaction between other sectors like fuel supply and transportation.

ReDES is single-sector rather than a multiple-sector model and does not consider interaction between a power system and other related industries like fuel supply and transportation. In not considering the fuel-supply system, ReEDS only performs a single-sector optimization instead of co-optimization of the combined power and fuel-supply systems.

2. 2 year basis optimization can not cover 40 overall optimization

ReDES sequentially performs a 2-year-basis optimization until the end of the planning year. The objective of such an optimization is the 2-year investment cost plus 20-yearoperational cost for all capacity. While there are benefits of using a 2-year-basis optimization, its disadvantage is that a 2 year base objective function cannot cover the total production cost for the entire planning horizon. Therefore, investment decisions are not based on minimization of the 40-year total cost.

3. Transmission planning has not been implemented. Transmission constraints and upgrade within control area is neglected

Although ReEDS can support transmission planning, it does not currently consider the replacement of existing or new transmission infrastructure. Only the grid interconnection costs for new generators are represented in the objective function.

It is assumed in using PTDF to calculate power flow along transmission lines over a control area that there are no thermal and voltage reliability issues within that area. However, power injection to or withdrawal from outside the control area may cause congestion and voltage reliability issues within that area. It is more reasonable to incorporate the investment cost for upgrading the transmission lines within the control area in the objective function when transmission upgrading is implemented.

3.5 Possible Improvements of NETPLAN

The above model comparison shows both similarities and differences among NETPLAN, NEMS, and ReEDS. Some features are shared by the three models; some features are unique in NETPLAN; other features are not included in NETPLAN but could be possibly added as improvements. Possible improvements are listed as follows:

1. Model EPA regulations and compliance strategies on power system resource planning.

NETPLAN can add emission constraints on fossil-fuel power plants in accordance with existing environmental regulations. However, new environmental regulations have been proposed requiring fossil power plants to install emission control equipment in 2015. These requirements will increase the operational and investment costs of fossil-fuel power plants and, as a result, may change generation portfolios in the future. NETPLAN must be improved to represent these proposed environmental regulations. The implementation of this improvement is described in CHAPTER4 and CHAPTER5 in this thesis.

2. Models storage devices in load shifting, wind surplus saving, and reserve services.

Currently, storage is not modeled in the electrical sector. A storage model could be used in the future to reflect wind surplus saving, resource firming and ancillary services. The economic analysis of using storage to offset the variability of wind energy could also be performed using a more details time frame in NETPLAN.

3. Reflects market behaviors, such as fuel supply curve and demand response.

By incorporating market behavior, a more reasonable result could be made using LP method. Fuel supply curve could be modeled by using multiple supply arcs. Demand response could be modeled to reflect load shifting and interrupted demand during on peak hours.

4. Relates generation technologies to base load, intermediate load, and peak load.

There are two ways of using load duration curve in the resource-planning model. The first is to divide load duration curve vertically, as is currently done in NETPLAN. The second is to divide load duration curve horizontally. This latter approach has the advantage of relating types of generation technologies to base load, intermediate load, and peak load. For example, nuclear and hydro are only utilized during the base-load period. Natural gas and oil units are used for peak hours. The strategy can limit over-generation of nuclear and under-generation of natural gas in NETPLAN.

5. Incorporates both unplanned outage and scheduled outage.

Forced outage could be modeled either as an event occurring in the resilience index or in an uncertainty model. Maintenance is currently not represented in the NETPLAN model. An approximate method is to decrease available capacity by a certain amount to offset the factor. Another method is to add scheduled maintenance constraints to reflect maintenance issues.

CHAPTER 4: EPA REGULATIONS

This chapter focuses on the implementation of environmental issues in NETPLAN. Emission control equipment, such as a Flue-Gas Desulfurization (FGD), a Selective Catalytic Reduction (SCR), and a Carbon Capture and Sequestration (CCS) are modeled. Emission constraints include national and regional level SO_2 and NO_X caps. Fossil-fuel power plants must be designed to choose compliance strategies that reduce emissions, including investing new power plants with low emission rates, retrofitting emission control equipment in existing power plants, changing dispatch methodology, switching fuel types, and earlier retirement.

4.1 Existing EPA Regulations

To add emission constraints and compliance strategies to NETPLAN, we must first understand environmental regulations issued by the Environmental Protect Agency (EPA). The EPA is responsible for establishing environmental policy to protect the environment. It is important for NETPLAN to incorporate EPA regulations, because these regulations may change the output of generation portfolios. Both existing environmental regulations and proposed environmental regulations are introduced in this chapter.

Existing Emission Regulations

The existing emission requirements have multiple levels. They include emission cap-and-trade programs at the national or regional level. EPA also establishes specific requirements at the state or unit levels[30]. In this chapter we will stress national and regional emission regulations with respect to SO_2, NO_X, and CO_2. There are two important cap-and-trade programs[6] regarding SO_2 and NO_X, and both are included in the resource planning model used by NEMS[5] and IPM[8].

One of emission regulation programs is Clean Air Act Amendments (CAAA) issued in 1990, which sets a goal of reducing annual SO_2 emissions by 10 million tons below 1980 levels. It affects all SO_2-emitting fossil-fuel generating units with capacities greater than 25 MWs; Both cap-and-trade programs and banking allowances[7] are included in CAAA. The annual national level SO_2 cap is 8.95 million tons [30].

The other program is the NO_X SIP Call trading program, which affects all NO_X-emitting fossil-fuel units in 20 northeastern states and the District of Columbia. This program is only in effect during the ozone season (May - September). The total annual NO_X SIP Call is 527,580 tons[30].

There is at the present time no nationwide constraint on CO_2 emission. The only regional regulatory program is The Regional Greenhouse Gas Initiative (RGGI). It covers 15 Northeastern and Mid-Atlantic states and has as a goal reduction of power-sectorCO_2 emissions by 10 percent by 2018[30].

According to EPA's data, fossil-fuel power plants are responsible for 67 percent of the nation's sulfur dioxide emissions, 23 percent of its nitrogen oxide emissions, and 40 percent of its man-made carbon dioxide emissions[31]. Table 4-1 shows the average emission rate produced by the various types of power plants. Coal power plants have the

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6. A cap-and-trade program first sets a maximum limit on emissions. Sources covered by the program then design its own compliance strategy to meet the overall reduction requirement, including the sale or purchase of allowances, installation of pollution controls, and implementation of efficiency measures, among other options. http://www.epa.gov/captrade/basic-info.html

7.Banking of allowances allows sources to save excess allowances for future time periods. It could increases the efficiency of a cap-and-trade program by shifting reductions to lower-cost time periods and smoothing price variations between different allowance periods. http://www.rff.org/documents/RFF-DP-10-42.pdf highest emission rates of carbon dioxide, sulfur dioxide, and nitrogen oxides. For that reason, coal-fired boilers are required to install control equipment for reducing emissions. Natural gas power plants produce half of carbon dioxide emission, less than one third of nitrogen oxide emission, and one percent of sulfur oxides emission compared to coal power plants. Wind, solar, hydro, and geothermal power plants do not release any of these three emissions because no fuels are burned. Biomass power plants emit nitrogen oxides and a small amount of sulfur dioxide. “The amounts emitted depend on the type of biomass that is burned and the type of generator used. Although the burning of biomass also produces carbon dioxide, it is considered to be part of the natural carbon cycle of the earth” [31].It is clear that coal and oil power plants are the main objective focus in reducing emissions.

Table 4-1. Average emission rate by the type of power plants

	SO_2	NO_X	CO_2
Coal	13 lbs/MWh	6 lbs/MWh	2,249 lbs/MWh
Natural gas	0.0 lbs/MWh	1.7 lbs/MWh	1135 lbs/MWh
Oil	12 lbs/MWh	4 lbs/MWh	1672 lbs/MWh
Municipal solid waste (MSW)	0.8 lbs/MWh	5.4 lbs/MWh	2988 lbs/MWh
Nuclear	N/G	N/G	N/G
Wind/Solar/Hydro/Geothermal	N/G	N/G	N/G
Biomass/Land fill	--	--	N/G

Emission control equipment could be used to reduce SO_2, NO_X, and CO_2 emissions. Table 4-2 shows the alternatives for emission-control technologies. There are two options for SO_2 emission reduction. Limestone Forced Oxidation (LSFO) is a wet FGD technology capable of reducing 95% of SO_2 emission. The Lime Spray Dryer (LSD) is a dry FGD technology with 90% reduction. The installation of LSD will be limited since LSD removal efficiency drops significantly for high sulfur content coal [32]. The technologies available for NO_X reduction include both combustion controls and post-combustion controls. Combustion controls reduce the NO_X during the combustion process and has a reduction rate ranging from 10% to 50%. They have been installed in existing power plants but will not be installed in future coal power plants [32]. Post-combustion control of course operates following the combustion process. Two post-combustion technologies are SCR with catalyst and SNCR without catalyst. Due to the use of a catalyst, SCR can reduce NO_X emission by 80%-90%, a much higher value than for SNCR (35%-50%). Both technologies are available to new coal power plants. For Hg control, two Activated carbon injection (ACI) technologies are available. The emission of Hg could also be reduced during the same process that reduces the emission of SO_2 and NO_X. Carbon Capture and Sequestration (CCS) is installed to reduce the CO_2 emission.

Table 4-2. Emission control technologies

SO_2 Control Technology Options	**NO_X Control Technology Options**	**Hg Control Technology Options**	**CO_2 Control Technology Options**
Limestone Forced Oxidation (LSFO) Scrubber (wet FGD,95% reduction rate)	Selective Catalytic Reduction (SCR) System	Standard Activated Carbon Injection (SPACACI) System	CO_2 Capture and Sequestration
Lime Spray Dryer (LSD) Scrubber (dry FGD, 90% reduction rate)	Selective Non Catalytic Reduction (SNCR) System	Modified Activated Carbon Injection (MPAC-ACI) System	
	Combustion Control	SO_2 and NO_X Control Technology Removal Cobenefits	

Source: Emission Control Technologies, Integrated Planning Model (IPM), EPA [32]

4.2 Proposed EPA Regulations

In addition to existing emission regulations, several proposed environmental regulations will be implemented between 2015 and 2018[33]. These proposed regulations may result in earlier retirement of fossil fuel power plants, especially older and smaller coal power plants. Two criteria are used in deciding for earlier retirement. One criterion is likelihood of retrofitted power plants achieving positive cash flow during their lifetime. The second is if the cost of compliance is higher than the cost of power plant replacement [33].

Maximum Achievable Control Technology Standard (MACT)requires all existing coal-fired and oil-fired power plants to reduce their emission of air toxins, including mercury, acid gases, and heavy metals[33]. MACT stresses emission-control requirements on unit-level power plants. This may cause power plants to retrofit corresponding emission control equipment such as FGD, SCR, and ACI. Table 4-3 shows the emission control equipment needed for coal power plants using different types of coal. According to MACT, for power plants using bituminous coal, Flue-Gas Desulfurization (FGD) and Selective Catalytic Reduction (SCR) are needed if a plant has no emission control. For power plants using Sub-Bituminous and Lignite Coal, Flue-Gas Desulfurization (FGD) and Activated Carbon Injection (ACI) are needed. It is assumed that the deadline for MACT compliance is January 1, 2018.

Table 4-3. Emission control equipment required by MACT

	BIT	Sub-BIT	LIG
FGD	add	add	add
SCR	add		
ACI		add	add
Baghouse (Fabric Filters) [8]		add	add

Source: Resource adequacy impacts of potential us environmental regulations, NERC.

[8]Baghouses are air pollution control devices used to control particulate emissions from stationary sources. http://www.epa.gov/etv/pubs/600r07029.pdf

Clean Air Transport Rule (CATR) was proposed on July 6, 2010 by the EPA. It created a new annual NO_X cap-and-trade program and modified the existing SO_2 cap-and-trade values for 28 states. CATR would regulate SO_2 and NO_X emissions under annual SO_2, annual NO_X, and seasonal NO_X cap-and-trade programs[33]. According to CATR, by 2014 power plants would reduce SO_2emission by 71 percent and NO_X emission by 52 percent below 2005 levels [34]. Since CATR limits out-of-state allowance purchases and bank allowance before 2014 are useless, fossil-fuel power plants must retrofit FGD or SCR emission controls. Otherwise, they must retire. Figure 4-1 shows the regions affected by CATR.

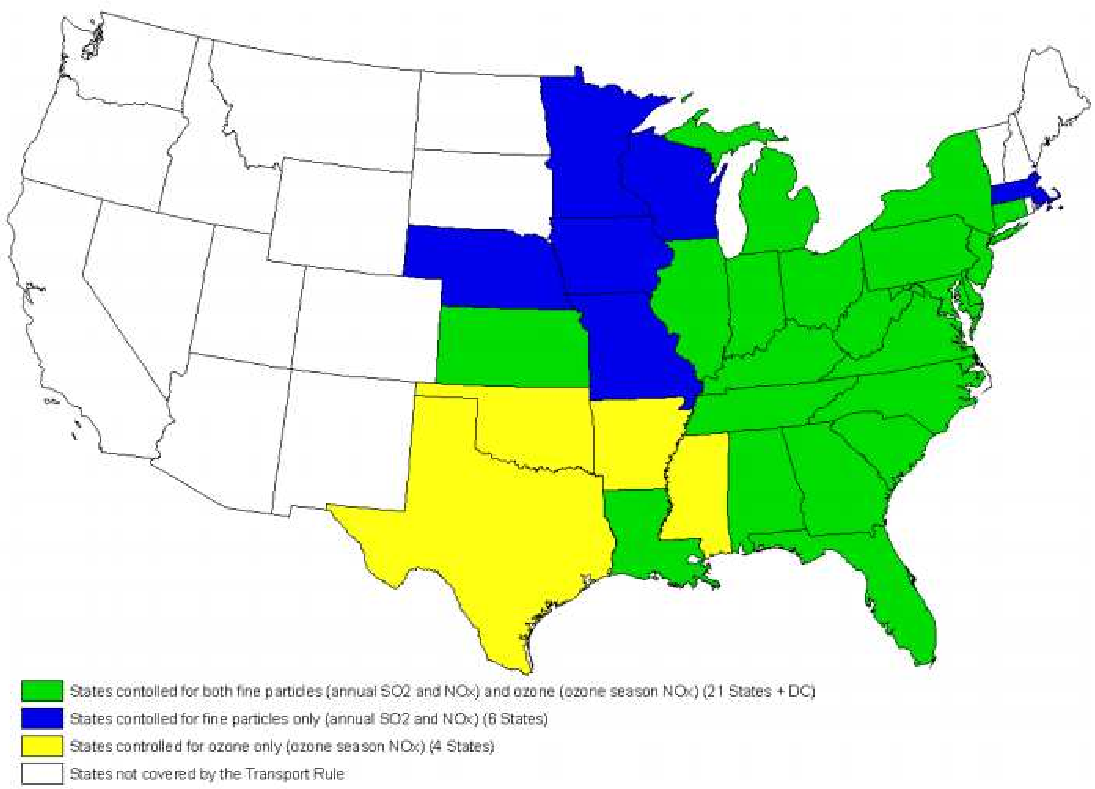

Figure 4-1. States control on SO_2 and NO_X in CATR[34]

Two other proposed Environmental Regulations are the Cooling Water Intake Structures and the Coal Combustion Residuals (CCR) Disposal Regulations. The former requires power plants (fueled by coal, gas, and nuclear) to replace existing open-loop cooling systems with closed-loop cooling systems. The latter proposed two alternatives for coal-fired power plants for regulating disposal of coal combustion products. Both these two regulations may cause retirement of existing power plants if it is not economic to operate them[33].

Figure 4-2.States projected timeline for regulation development and implementation [35]

The above figure shows the status of four proposed EPA regulations. The Cross-State Air pollution Rule, originally supposed to be a substitute for the clear Air Transport Rule, was vacated in Aug. 2012 [36]. Mercury and Air Toxic Standards, also known as MACT, will be implemented in 2015. The Clean Water Act may become effective in June 2013. Implementation of compliance is scheduled for 2018.Although NERC [35] lists a coal-combustion-residuals rule as one of the EPA regulations that may have an important impact on coal power plants, according to the latest report on EPA regulations [36], the status such a rule is unknown.

CHAPTER 5: NETPLAN MODELING EXTENSION

In this chapter, NETPLAN is improved to analysis of proposed environmental regulation impact. Compliance strategies include new power plants with low emission rate, retrofitting with emission control equipment, changing dispatch way, fuel switch and earlier retirement. A multi-level and multi-arc design is applied to model power plants retrofitted with emission control equipment.

5.1 Add Emission Caps as Side Constraints

In the NETPLAN model, energy flow is the only flow passing through the network, while emission is the byproduct of energy flow. The amount of emission depends on the fuel type, emission control equipment installed, and the amount of electricity produced. Adding emission constraints means that there is a limit on emission associated with energy flows along fossil fuel power plant arcs. Since a pure network-flow LP model could not represent such a relationship, a side constraint must be considered to do so.

Side constraints in the network-flow LP model are used to specify the relationships of several arcs in the network-flow model. They could be proportional constraints, blending constraints and multi-commodity problem constraints. The first two constraint types are usually applied to represent product processes. Multi-commodity problem constraints are used when there are limits on overall production or demand in multi-commodity, multidivisional, or multi-period problems [36]. Figure 5-1 shows how typical multi-commodity problem constraints can be used to combine the outputs of specific arcs to meet overall requirements or limits. For example,

$$Plt1_{NonFGD} \times 13 + Plt1_{FGD} \times 13 \times 0.05 + Plt2_{NonFGD} \times 13 + Plt2_{NonFGD} \times 13 \times 0.05 \leq 200$$

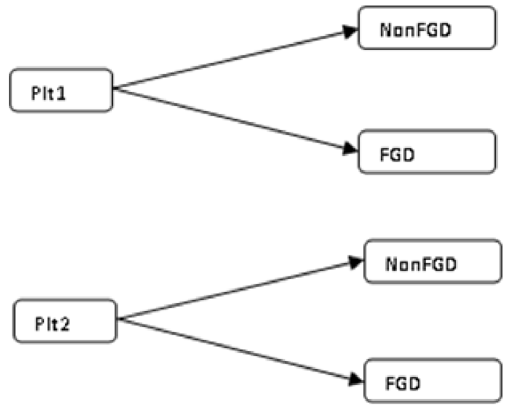

Figure 5-1. Multi-commodity problems constraint

Both national and regional emission limits could be represented in NETPLAN. However, state-level emission limits are currently not included in NETPLAN because our data is aggregated at the regional level. To represent proposed CATR regulation, state-level emission limits will be summed up to represent the national or regional level. It should be noted that such summation will permit allowance to be traded among states. However, the CART regulation is stricter because it will limit outside-state allowance.

After adding side constraints, the matrix of the network-flow LP model has more than two non-zero entries in each column, making it no longer a node-arc incidence matrix. The CPLEX software solver from ILOG will automatically recognize the embedded network structure, solve this portion using the network simplex algorithm, and then perform standard linear programming iterations on the full problem using the network solution to construct an advanced starting point[1].

5.2 Model Compliance Strategies in NETPLAN

Two types of compliance strategies are available to permit fossil fuel power plants to meet emission constraints. The first is to use investment strategies that include retrofitting emission control equipment in existing power plants and building new power plants with lower emission rates. Installing emission control equipment may result in earlier retirement if the investment cannot produce positive cash flow during the plant's lifetime or if the cost of compliance is higher than the cost of a plant. The other type of compliance strategies are operational options that include changing the amount of generation and fuel switching. In NETPLAN, all these potential options may be chosen based on minimum cost criteria.

5.2.1 Investing New Power Plants with Low Emission Rate

All new coal power plants are assumed to have installed emission control equipment to achieve compliance with EPA regulations. Since new coal power plants are different from old power plants in both operational cost and emission rate, they are defined as new arcs parallel to existing power plants, with one end of each with connecting to a coal network node. The parameters associated with the new power plants are investment cost, operational cost, maximum investment capacity, life span, and emission rates.

5.2.2 Retrofitting Existing Power Plants with Emission Control Equipment

NETPLAN currently allows retrofitting coal power plants with three kinds of emissions control equipment: FGD, SCR, and CCS. A coal power plant group has retrofit potential through a combination of FGD, SCR, and CCS. The choice of a retrofitting combination and the time to install such equipment depends on both the emission cap and the minimum cost criteria. Figure 5-2 shows a multi-level and multi-arc design representing power plants with potential emission control equipment. The physical meaning of the vertical design is to split the original power plant node into several nodes. In this case, energy flows that pass these nodes are equal, the difference being in the characteristics of the arcs that connect with these nodes. Each arc level represents a different emission control choice. Parallel multi-arcs at each level are used, since the energy flow could choose to pass the arc either with emission control or not. In this way, the emission controls are maintained independently of each other. Emission controls could thus be added at any level without interfering with other emission controls, permitting different choices of retrofitting combinations

Two details in Figure 5-2 should be stressed. First, because existing power plants could have either SCR or SNCR or both to control NO_X emission, two NO_X emission control arcs are modeled at the NO_X emission control level. Second, for SO_2 emission control, although emission control is added on the arc between the coal power plant node level 1 and level 2, the emission rate is added on the arcs between coal power plant node level 1 and coal network nodes. This is because different kinds of coal have different sulfur content

Retrofitting emission control equipment will decrease the power plant's maximum capacity and increase its heat rate. Therefore, when an emission control is installed, it will represent a negative contribution (capacity credit) to the peak load. At the same time, energy loss is added along the arc at which the emission control appears. The other parameters associated with emission control arcs are the current and maximum capacities of emission control equipment, investment cost, and incremental operational cost due to retrofitting emission control equipment.

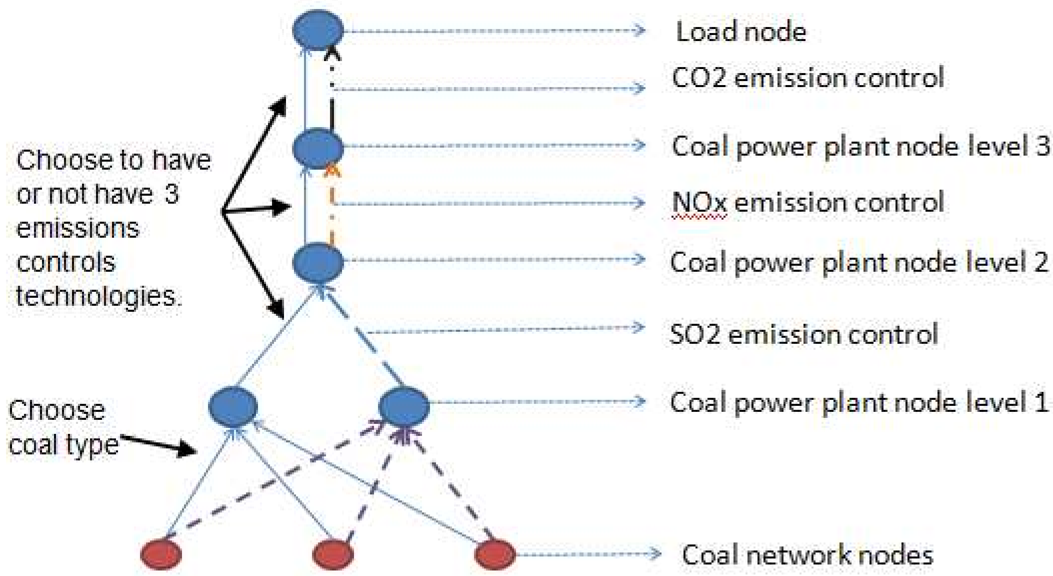

Figure 5-2. Retrofitting emission control equipment on existing coal power plants

The model design described in Figure5-2 is useful in assessing the impact of MACT regulations. We could, for example, let the capacity of arcs without FGD emission control to be zero after 2015, then let use NETPLAN determine the number of coal power plants in which installing FGD control would be economical. Since NETPLAN will produce a solution that minimizes the total cost, the capacities not installed with control are by implication not economical when compared with other replacements.

Because not all coal power plants are required to install SCR, the capacity of arcs without SCR will not be set to zero after 2015, and this design will cause a problem. Energy flow may choose to go through an arc without SCR first as long as the NO_X cap is not violated due to lower operational cost. Therefore, the installed SCR probably is not in use in some cases. The problem is not serious since it only causes a small reduction in the total cost, and could be remedied by post-correction using the output data of NETPLAN.

5.2.3 Changing Dispatching Approach

Emission constraints could be achieved by adjusting operational dispatch. This is easy to understand because the emission amount is closely related to the amount of the energy produced and when energy flows decrease, the emissions are also decreased. In NETPLAN, generation flows are decision variables of the network-flow LP model, so generation flows could be adjusted to comply with the emission constraints.

5.2.4 Fuel Switch

The strategy of fuel switch can only be effective for SO_2 emission. Unlike NO_X and CO_2 content that remain constant among the different coal types, sulfur content among the types of coal varies greatly. The common sulfur content in coal measured by weight ranges from 0.4% to 4%[38], so, changing coal type can reduce the SO_2 emission significantly.

In NETPAN, fossil-powered plants are connected with fuel-supply nodes. The model considers four types of coals so that four arcs connected to different types of coal supply are generated. SO_2 emission rates are assigned on these arcs so that different amounts of sulfur content could be identified.

The fuel-network location must align with the power-plant location so that the amount of the fuel delivered to a specific destination could be converted to energy generation. Fuel transportation entities are identified by state location, and these state nodes are then converted to the NERC region. As a result, the power plants in one NERC region share the sum of fuel supply of the several states that belong to one NERC region. Transportation cost within the NERC region is neglected.

5.2.5 Earlier Retirement

Among EPA's proposed regulations, the MACT, ash, and water regulations are command regulations that require units to make a binary decision to either meet the requirements or shut down. In contrast, CATR are market-based cap-and-trade mechanisms [39]. Different criteria are defined for determining whether or not to retire a power plant. Several studies addressing earlier retirement because of EPA-proposed regulations are introduced below, and treatment of earlier retirement in NETPLAN is then discussed.

IPM

In IPM, "an existing power plant that cannot recover its fixed costs of operation on an ongoing basis will be retired" [39]. Under environmental regulations, existing power plants will be allowed to install control investments to prolong their lifetimes. IPM will compare the cost of installing control equipment with future revenues that plant might earn. Another economically-based comparison is made between existing power plants that install emission control equipment and building a replacement power plant. IPM will assess retirement and capacity resource expansion based on the minimum cost function over the entire planning horizon.

NEMS

The Electricity Capacity Planning (ECP) module in NEMS is able to evaluate whether it is more cost effective to continue or to replace existing operating units with new capacity responses to environmental regulations [19]. In NEMS, power plants are retired according to scheduled dates, and remaining units are available for retirement based on the minimum cost function over the entire planning horizon. If the ECP determines that it is not cost-effective to continue using this capacity, the value of operating units will be less than the available capacity.

NERC's retirement studies

NERC adopts an economic approach from Energy Venture Analysis Inc (EVA) to identify which units may retire if a generic required cost of compliance due to proposed environmental regulation exceeds the cost of replacement power. The replacement power was considered to be produced by gas-fired generation [33]. Then NEMS is run to determine earlier retirements beyond the scheduled retirements determined by EVA models.

NETPLAN

For MACT regulation, the existing capacity is evaluated for possible exclusion of capacities that are non-economical due to MACT. NETPLAN will define two arcs, one havingSO_2 emission control, while the other has none. Beginning in 2015, the capacity of arcs without SO_2 emission control for coal power plants are assigned values of zero, so the only way to use existing coal power plants is to install FGD on the arcs with SO_2 emission control. NETPLAN will determine if it is economical to install emission control equipment by comparing the existing situation with alternative generation technologies. The difference between the capacity of power plants with FGD and the available coal power plants will indicate desirability of retirement due to the MACT.

For CATR regulation, NETPLAN will determine installing emission control equipment and adjust the coal power plants' dispatch method to comply with emission caps set by CATR. If the power plants are represented at a unit level, a power plant could be considered for retirement if no more energy flows through the power plant arc. If the power plants are represented a group, since the capacity of coal power plants will not disappear until the announced retirement date, we cannot determine retirement from capacity.

5.3 Modification of NETPLAN

Installation of environmental equipment to power plants will add investment cost, increase operational cost, decrease maximum capacity, and cause energy loss. Therefore, such installation requires changes in the math expression of NETPLAN, including objective function, peak load reserve margin constraints, flow constraints, and emission constraints.

Objective function

$$\min\{CostOp^{E} + CostInv^{E} + CostInv^{E}_{emission} + CostOp^{T} + CostOp^{E}_{emission} + CostFleetInv^{T} + CostInfInv^{T}\}$$

Where,

$$CostOp^{E}_{emission} = \sum_{t}\sum_{(i,j)}(1+r)^{-t}costOp^{E}_{emission(i,j)}(t)e_{emission(i,j)}(t)$$

$$CostInv^{E}_{emission} = \sum_{t}\sum_{(i,j)}(1+r)^{-t}costInv^{E}_{emission(i,j)}(t)eCap_{emission(i,j)}(t)$$

$e_{emission(i,j)}$:Electric flow passing emission controls

$eCap_{emission(i,j)}$: Capacity retrofitted with emission controls

In the objective function, $CostInv^{E}_{emission}$ represents the retrofitting costs of emission control equipment. $CostOp^{E}_{emission}$ representsincremental costs due to the operation of emission control equipment.

Modification of constraints

Peak load reserve margin constraints reflect capacity penalty:

$$\sum_i cc_{(i,j)}(t)eCap_{(i,j)}(t) - cc_{emission(i,j)}(t)eCap_{emission(i,j)}(t) \geq rm_j^E(t)peakD_j^E(t), \;\; j \in N_p^E$$

In the equations reflecting peak load reserve margin, a negative contribution $cc_{(i,j)}$is added to arcs with emission control equipment to reflect the capacity penalty.

Flow constraints at power plant nodes reflect heat rate penalty due to FGD, SCR, and CCS operation:

$$\sum_i e_{(i,j)}(t) + \eta_{emission(i,j)}(t)e_{emission(i,j)}(t) - \sum_i e_{(j,i)}(t) = 0$$

For power plants represented at the aggregated level, electricity flow may go through both arcs without emission controls and arcs with emission controls. $e_{(i,j)}(t)$ represents electricity flow going through arcs without emission controls. $\eta_{emission(i,j)}(t)e_{emission(i,j)}(t)$ represents electricity flow going through arcs with emission controls. $\eta_{emission(i,j)}(t)$ represents energy efficiency of coal power plants, which accounts for the heat rate penalty due to operation of emission controls.

Emission Constraints reflect emission reduction

$$\sum_{t\in T}\sum_i ErSO2_i(t) \cdot e_{(i,j)} + ErSO2_i(t) \cdot (1-\alpha_i) \cdot e_{emission(i,j)} \leq LSO2_T$$

$$\sum_{t\in T}\sum_i ErNOx_i(t) \cdot e_{(i,j)} + ErNOx_i(t) \cdot (1-\beta_i) \cdot e_{emission(i,j)} \leq LNOx_T$$

$$\sum_{t\in T}\sum_i ErCO2_i(t) \cdot e_{(i,j)} + ErCO2_i(t) \cdot (1-\gamma_i) \cdot e_{emission(i,j)} \leq LCO2_T$$

Where,

i – node that represents the power plant;

j – destination node connecting with node i;

T – the time period to which that the emission cap. It could be one year or ozone months.

$SO2_i(t), NOx_i(t), CO2_i(t)$ are the emission contents in the fuel type. $\alpha_i, \beta_i, \gamma_i$ are emission reduction rates due to installation of emission control equipment for SO_2, NO_X and CO_2 respectively.

For power plants represented at aggregated level, emission calculation includes emission from arcs with emission controls and arcs without emission controls. When electricity goes through arcs with emission controls, an emission deduction parameter is added to account for decrease in emission.

To represent emission controls in NETPLAN, new nodes and arcs are added during data preparation. These are summarized in Table 5-1.

Table 5-1. Summary of improved NETPLAN

System	Type	Size
Coal	Production	24 nodes
	Demand	49 nodes
Natural gas	Production	25 nodes
	Demand	50 nodes
	Pipelines	108 arcs
	Import pipelines	9 arcs
	Storage	30 nodes
Electricity	Generation	203 nodes
	Demand	13 nodes
	Generation	203 arcs
	Transmission	19 arcs
	Import transmission	8 arcs
Emission controls	FGD	52 arcs
	SCR/SNCR	26 arcs
	CCS	39 arcs
Emission constraints	SO_2	40
	NO_X	80
Petroleum	Gasoline	13 nodes
	Diesel	13 nodes
Freight	Transportation	95 arcs
	Coal demand	40 nodes
Passenger	Vehicles	13 arcs

CHAPTER 6: CASE STUDIES

In this chapter, the improved model will used to analyze the impact of EPA regulations on the generation portfolio over the planning horizon. Investment in environmental-control equipment, such as FGD, SCR, and CCS, is made to meet the emission cap constraints. Sensitivity analysis is performed to discover variations in the generation portfolio in response to the changes in investment cost, maximum investment capacity, carbon tax, and fuel price.

6.1 Assumptions and Input Data

The case studies in this chapter are based on the following assumptions:

Peak load and electricity demand

The initial peak load and electricity demand are obtained from 2009 EIA statistics data [40]. Since NETPLAN regions are different from current NERC regions, appropriate modifications were made when dealing with the EIA data. Electricity demand growth rate is set at 1% per year. As shown in the annual Energy Outlook [41], annual growth in electricity use is projected at about 1% from 2008 to 2035. The peak-load demand growth rate is set at 1.5% each year. The number is consistent with the results in the NERC report regarding peak demand forecast bandwidths [42], which range from 1.1% to 3% over the years 2008-2016. The peak-load growth rate is set relatively low due to energy considerations, efficiency improvement, and the demand response program in the long term. A constant peak load growth rate for each region is used in our study; a further study could set different peak load growth rates for different region.

The peak load demand also includes reserve margin. Reserve margin for every region comes from NERC requirement.

Retirements and outage rates of units

Power plant retirements occur as input data to NETPLAN. The outage rates of units include both scheduled and unplanned outage. Scheduled outage represents the power-plant scheduled maintenance. Unplanned outage represents forced outage due to facility failure or breakdown. The forced outage could also be modeled as events during resilience analysis, or treated as a random variable conforming to a specific probability distribution in an uncertainty model. Maintenance is not currently represented in the NETPLAN model, and an approximate method for dealing with it would be to derate the total available capacity by a certain amount.

Cost and characteristics of generation technologies

Table6-1 shows the cost and related characteristics of various generation technologies taken from EIA and representing the most up-to-date data [43]-[46]. Cost and performance data of power plants include overnight cost, O&M cost, fuel cost, capacity factor, and lifetime.

As shown in the Table 6-1, new generation technologies like geothermal, tidal, and solar PV have the highest investment cost. Fossil-fuel power plants using natural gas and oil have the highest fuel cost. Since the objective function includes both investment cost and operational cost, tradeoffs will be made between both kinds of cost to find the minimum cost of meeting both electricity demand and reliability requirements. Currently, fixed cost is not included in NETPLAN, but since it tends to have positive correlation with investment cost it will not significantly affect the results.

Table 6-1. Characteristics of generation technologies

Plant type	Overnight cost ($/KW)	O&M cost ($/MWh)	Fuel cost ($/MWh)	Capacity factor	Lifetime (Year)	Max inv per year (GW)
Nuclear	6084.54	2.35	2.56	0.9	60	7.8
Hydro	5857.6	2.83	0	0.4	100	0
Pulverized Coal	2967.00	4.40	20.08	0.7	40	13
IGCC	4545.80	12.10	15.67	0.8	40	13
Geothermal	10313.55	9.00	0	0.8	50	6.5
Inland Wind	2035.13	0.00	0	0.1-0.5	25	19.5
Offshore Wind	4069.35	0.00	0	0.2-0.4	25	2.5
IPCC	6838.43	11.80	--	0.7	30	13
Tidal Power	8068.20	9.00	0	0.3	50	8.75
Oil	2125.07	3.04	40.94	0.2	30	13
NGCC	978.00	2.59	50.93	0.4	30	26
CT	972.50	3.65	71.70	0.2	30	13
Solar PV	7210.33	0.00	0	0.1-0.25	30	19.5
Solar Thermal	6056.87	2.80	0	0.1-0.25	30	19.5

When the load duration curve (LDC) is not applied, capacity factors for traditional generation technology are used. The use of capacity factors could reduce generation from hydro and coal power plants and, as a result, increases generation from natural gas power plants. When the LDC is applied, there is no need to add a capacity factor for traditional generation technology since the utilization of power plants could be identified by the segments of the LDC. For intermittent resource like wind and solar, capacity factors are always needed to represent variability of the energy supply.

The maximum investment capacity for each year is defined for each region. As we will see in the sensitivity analysis later in this chapter, the upper limit of investment capacity will significantly affect the generation portfolio.

Treatment of wind variability

Wind variability is represented in NETPLAN by introducing the concepts of capacity factor and capacity credit. Capacity factor is defined as average expected output of a generator as a percentage of the nameplate capacity over an annual period. It is used to limit the maximum generation from wind resources each year. Capacity credit is used to describe the contribution of capacity for intermittent resource to meet the peak load demand. Since the wind resources vary among different regions, different capacity factors and capacity credits are specified for each region. Two further improvements are possible. One would be to define maximum investment capacity for each region according to the available area for wind-capacity construction, and the other would be to add an operational reserve margin constraint that ensures that the spinning reserve and the quick-start reserve could meet the additional operational reserve margin imposed by the wind energy supply.

Emission control equipment

Tables 6-2 through6-4 show the investment cost, operational cost, and reduction rate of emission control equipment. Among such equipment types, CCS has a much higher investment cost, heat-rate penalty, and capacity penalty than FGD and SCR.

Emission controls for mercury are not included because the control for Mercury is always at the state or even at the unit level that NETPLAN currently cannot deal with. Also, the investment and operational cost of mercury control are less than those for SO_2, NO_X and CO_2 controls. For example, a 500 MW coal power plant only requires a $2/KW investment cost and 0.17 mills/kWh operation cost for mercury control [32].

Table 6-2. Characteristics for emission control equipment

	FGD[9]	SCR[1]	SNCR[10]	CCS[2]
Heat rate penalty	+1.5%	+1.5%	+0.05%	+33%
Capacity penalty	-1%	-1%	-0.05%	-10%
Removal rate	Wet:95%Dry: 90%	85%	35%	85%

Table 6-3. Investment cost for emission control equipment

$/KW	FGD	SCR	SNCR	CCS
Pulverized coal(500 MW)	420	400	75	1932
IGCC	420	400	N/G	1783
NGCC	N/G	--	N/G	1057

Table 6-4. Operation cost for emission control equipment

$/MWh	FGD	SCR	SNCR	CCS
Pulverized coal (500 MW)	3.00	3.00	2.30	5.00
IGCC	3.00	3.00	N/G	3.00
NGCC	N/G	--	N/G	3.00

It should be noticed that investment cost and operational cost of emission control equipment varies with capacity. The larger the capacity of a fossil fuel power plant, the less expensive (per KW capacity) the emission control equipment. Since power plants are modeled at the regional level in this study, capacity information has not been available, so costs for a typical 500 MW fossil fuel power plant was used.

6.2 Minimized-Cost Solution

Scenarios design

Five scenarios are defined for using NETPLAN to analyze the impact of existing and proposed emission regulations on generation portfolio results. In the reference scenario no

9EPA Regulation Impact Analysis Input Discussion, MISO, December 15, 2010

10 Documentation for EPA Base Case v.4.10 Using the Integrated Planning Model, EPA August 2010

emission regulation is imposed and new coal power plants are therefore not required to install emission control equipment. Beginning with scenario 1, new coal power plants are required to install FGD and SCR.

In scenario 1, existing SO_2 and NO_X cap-and-trade programs, CAAA SO_2cap-and-trade program and NO_XSIP Call trading program [30], are added.

In scenario 2, proposed environmental regulation CATR is partially represented. According to the proposed CATR[34][47], new SO_2 and NO_X emission caps will require 71% reduction of SO_2 emission and 52% reduction of NO_X emission from 2005 levels. Since power plants are currently modeled at the regional level, state emission cap-and-trade programs have limited availability. We will therefore use national SO_2 and NO_X cap-and-trade programs and regional level Ozone NO_X cap-and-trade programs as substitutes for CATR regulation.

In scenario 2, proposed environmental regulation MACT is partially represented. All coal power plants are required to install FGD after 2015. SCR is optional for coal power since only those coal power plants using BIT type coal are required to install SCR. Other emission control equipment required by MACT, including ACI (Hg), Baghouse (FF), Coal Combustion Residuals, and Cooling Water Intake Structures are not included. The full representation of MACT depends on obtaining more detailed input data for power plants.

In scenario 3 and scenario 4, since there is no CO_2 cap described in the proposed emission regulations, a carbon tax is set to $50/Ton and $30/Ton, respectively. Coal power plants and natural gas power plants can optionally install CCS. A case study using a carbon tax of$20 /Ton is also given in the sensitivity analysis.

Table 6-5. Scenario design

Scenario	Description
Reference Case	No emission cap. No requirement for emission controls.
Scenario 1	Existing emission caps on SO_2 and NO_X.
Scenario 2	New emission caps on SO_2 and NO_X. All existing coal power plants are required to install FGD and optional to install SCR, starting in 2015.
Scenario 3	Scenario 2 + Carbon tax $30/Ton
Scenario 4	Scenario 2 + Carbon tax $50/Ton

Computation was performed on an Iowa State University server with a 1.6 GHz processor and 24 GB of RAM memory. C++ libraries for ILOG CPLEX 12.2 [14]were used to solve the linear programs. Solution times for the full problem without decomposition averaged 17 minutes. The first-year simulation of the reference case is shown in Table 6-6 and Table 6-7.

Table 6-6. Actual generation versus simulation results (%)

	Coal (%)	NG (%)	Hydro (%)	Nuclear (%)	Renewable (%)	Others (%)	Total (%)
2009	44.4	23.3	6.9	20.2	3.7	1.5	100
Ref	43.4	24.3	7.0	21.0	3.4	0.8	100

Table 6-7. Actual emission versus simulation results (Metric Tons)

	CO_2 (M/T)	SO_2 (M/T)	NO_X (M/T)
2005	2,543,838,163	10,339,543	3,961,097
2009	2,155,707,429	5,374,293	2,080,271
Ref	1,973,070,000	5,776,182	3,223,800

The first-year reference-case simulation shows that the percentages of generation from main energy resources are quite close to actual 2009 data. Emissions of CO_2 and SO_2 in the reference case seem relatively reasonable when compared with 2009 data. Because no NO_X emission limit is imposed, some SCRs are not active to reduce operational cost. Therefore, NO_X emission is greater than reflected in the 2009 data.

Table 6-8 shows the total capacity and corresponding total cost for five scenarios. Sce4 (with carbon tax of$50/ton imposed) has the highest cost. The reference case (no emission controls) has the lowest cost. From the reference case to scenario 4, the costs increase gradually because the environmental regulations become stricter. Sce4 also has a higher total capacity than other cases. A more detailed analysis reflecting the capacity difference among different cases will be given in Table6-9 and Table6-10.

Table 6-8. Total capacity and cost

	y5 (GW)	y10 (GW)	y20 (GW)	y30 (GW)	y40 (GW)	cost (T$)
Ref	988.0	1039.3	1247.4	1347.5	1586.3	3.2333
Sce1	988.1	1051.4	1278.6	1385.6	1632.7	3.2365
Sce2	987.8	1051.1	1277.9	1386.9	1634.1	3.2585
Sce3	1003.0	1079.6	1330.5	1464.5	1689.7	4.1423
Sce4	1009.3	1085.0	1334.6	1475.4	1735.6	4.6579

Table 6-9 shows that the percentage of fossil-fuel capacity continues to decrease over a 40-yearplanning interval in all cases. In contrast, Table 6-9 shows that the percentage of renewable capacity exhibits the opposite behavior in all cases. Nuclear capacity remains around 10% in all cases. For all scenarios, the percentage of renewable capacity over the 40-year planning interval increases from 13.8% to 25.1%, indicating that renewable resources become more and more economically attractive as environmental regulations become stricter.

Table 6-9. The percentage of fossil fuel capacity

	y1	y10	y20	y30	y40
Ref	77.9%	74.1%	73.7%	74.7%	75.6%
Sce1	77.9%	72.1%	70.0%	70.9%	71.7%
Sce2	77.9%	72.1%	70.1%	71.0%	71.7%
Sce3	77.9%	68.5%	64.4%	64.0%	67.2%
Sce4	77.9%	67.6%	63.7%	63.5%	65.2%

Table 6-10. The percentage of renewable capacity

	y1	y10	y20	y30	y40
Ref	11.8%	12.8%	12.4%	12.4%	13.8%
Sce1	11.8%	15.0%	16.4%	16.4%	17.9%
Sce2	11.8%	15.0%	16.3%	16.4%	18.0%
Sce3	11.8%	18.9%	22.5%	24.1%	22.9%
Sce4	11.8%	19.9%	23.3%	24.7%	25.1%

Table 6-11 shows the fossil-fuel capacity components at planning year 40 for five scenarios. At planning year 40, the percentage of pulverized coal (PC) capacity decreases from 28.9% to 13.7% over all scenarios, resulting in a decrease of the total percentage of coal capacity (existing PC, new PC and integrated gasification combined cycle (IGCC)) from 37.4% to 22.8%. In contrast, the percentage of Natural Gas Combined-Cycle (NGCC) and Combustion Turbine (CT) capacity increases from 55.0% to 67.1%.

Table 6-11. Fossil fuel capacity component at planning year 40

	Ref	Sce1	Sce2	Sce3	Sce4
Existing PC	0.8%	0.8%	0.8%	0.8%	0.8%
New PC	28.9%	21.3%	21.2%	12.2%	13.7%
IGCC	7.7%	9.1%	9.1%	9.5%	8.2%
IPCC	1.7%	1.8%	1.9%	2.5%	3.6%
Oil	6.0%	6.1%	6.1%	6.5%	6.5%
NGCC	30.3%	33.4%	33.4%	38.1%	37.6%
CT	24.7%	27.5%	27.5%	30.2%	29.5%
Total	100%	100%	100%	100%	100%

Table 6-12 shows the renewable capacity components at planning year 40 for all cases. Inland wind has the biggest market share and the second largest capacity is traditional hydro. In sce3 and sce4, investment in geothermal and tidal power is made after wind reaches its maximum investment capacity.

Figure6-1 shows the percentage of renewable capacity changing over the 40 planning years. As shown in Figure6-1, the percentage of hydro capacity decreases because there is no new investment in traditional hydro resources and hydro capacity remains the same although the total renewable capacity increases. Figure 6-1 also shows that wind capacity reaches its peak around year 25 and then begins to decrease. This is because a large amount of wind capacity is retired and the maximum wind-capacity investment of is limited. The rate of new investment capacity could not keep up with that of retirement.

Table 6-12. Renewable capacity component at planning year 40

	Ref	Sce1	Sce2	Sce3	Sce4
Hydro	25.9%	26.0%	26.0%	26.0%	19.6%
Inland wind	62.1%	62.1%	62.1%	62.1%	51.9%
off-shore wind	0.0%	0.0%	0.0%	0.0%	0.0%
Geothermal	7.4%	7.3%	7.3%	7.3%	12.9%
Tidal Power	3.3%	3.3%	3.3%	3.3%	15.2%
Oceanic Thermal	0.0%	0.0%	0.0%	0.0%	0.0%
PV Solar	0.5%	0.5%	0.5%	0.5%	0.0%
Solar Thermal	0.7%	0.7%	0.7%	0.7%	0.4%
Total	100%	100%	100%	100%	100%

Figure 6-2 shows the total investment of wind capacity over 40 planning years. The reference case has the lowest total investment capacity. Investment in wind capacity increases after coal power plants are required to install FGD and SCR and still more investment in wind capacity occurs after fossil fuel power plants experience carbon tax.

Figure 6-3 shows the differences in total wind-capacity investment among NERC regions over 40 planning years. These results show high investment in wind capacity in regions with a great amount of wind resources. Some regions, such as MAIN and MAPP, have the largest investment capacity of wind in reference case when no environmental regulations are imposed. In contrast, wind is not economical to install in regions such as RA and STV even after carbon tax is added. Other regions, such as MAAC, FL, and NWP will see a great increase in the wind investment after environmental regulations are implemented.

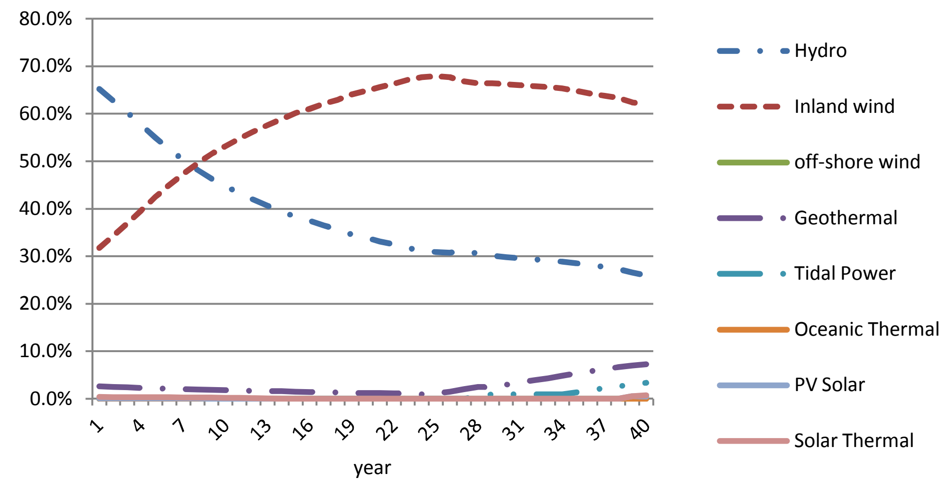

Figure 6-1. Percentage of renewable capacity changes in Sce2

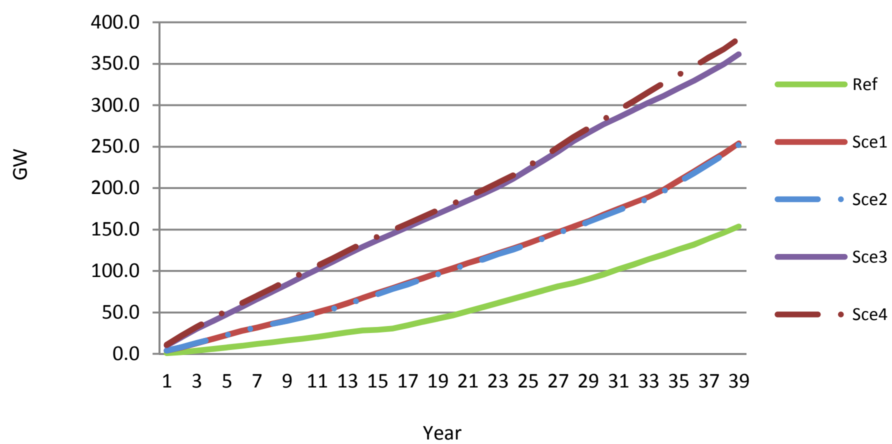

Figure 6-2. Total investment of wind capacity

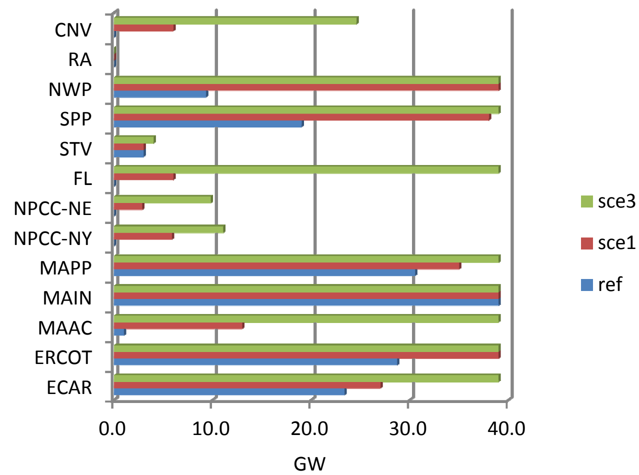

Figure 6-3. Total investment of wind capacity by regions over planning years

Table 6-13 shows the total FGD installation in Sce2. The largest FGD installation occurs in ECAR, SPP, and ERCOT and MAPP. It should be noted that the current regional division in NETPLAN refers to NERC regions before 2006, making the results differ slightly from other studies. Since existing PC plants with SCR and new coal power plants are capable of reducing NO_X emission to meet the new NO_X emission caps, no SCR installation is required in existing PC plants.

According to the proposed MACT, coal power plants without FGD will be retired after 2015. In Sce2, the existing capacity of coal power plants in year 2015 is set to 277.0 GW, assuming that 26.0 GW has already been retired by that time. The capacity of existing coal power plants with FGD is 180.5 GW. The result of installing 78.2 GW of FGD means that 18.3 GW of coal power plants must be retired early. If input retirement is added, the total retirement would be 44.3 GW. It is estimated by NERC [35] that the overall impact of combined EPA regulations on coal power plants will cause between 15.2 and 41.7 GW capacities to be retired by 2018.

Table 6-13. Installation of FGD in coal power plants in Sce2

	FGD installation (GW)	Percentage (%)
ECAR	21.9	33.3%
ERCOT	12.4	18.9%
MAAC	3.0	4.6%
MAIN	0.0	0.0%
MAPP	7.7	11.7%
NPCC-NY	0.0	0.0%
NPCC-NE	0.3	0.4%
FL	2.5	3.8%
STV	0.0	0.0%
SPP	17.6	26.9%
NWP	0.0	0.0%
RA	0.0	0.0%
CNV	0.2	0.3%
Total	78.2	100%

CCS equipment is installed in sce4 with a carbon tax of$50/MWh. No fossil fuel power plants will install CCS in sce3 when carbon tax is$30/MWh, meaning that carbon tax of 50 is an effective price incentive leading to investment in CCS.

Figure 6-4 shows that CCS equipment is installed starting in planning year 10. Most CCS equipment is installed in PC and IGCC coal power plants, and only a small number of NGCC power plants choose to install CCS. Figures 6-5, 6-6, and 6-7 show the capacity of CCS installed in different types of fossil-fuel power plants. At planning year 40, 78.7% of PC, 76.8% of IGCC, and 7.1% of NGCC must install CCS.

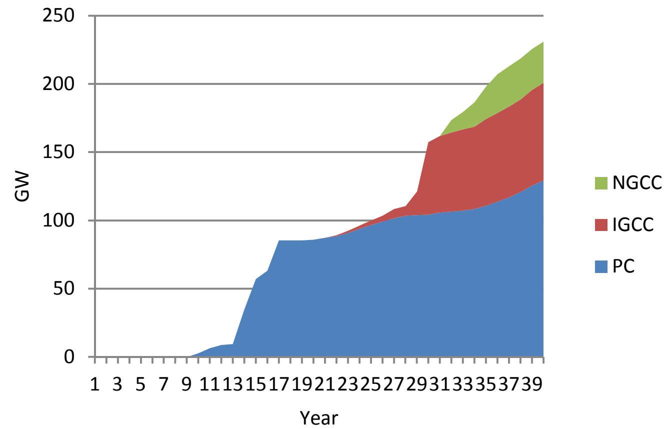

Figure 6-4. Total installation capacity of CCS in Sce4

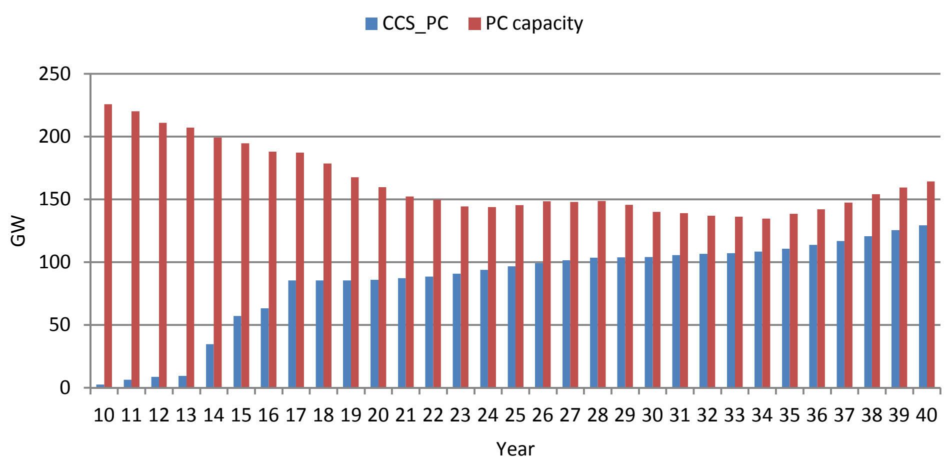

Figure 6-5. Capacity of PC with CCS VS capacity of PC in Sce4

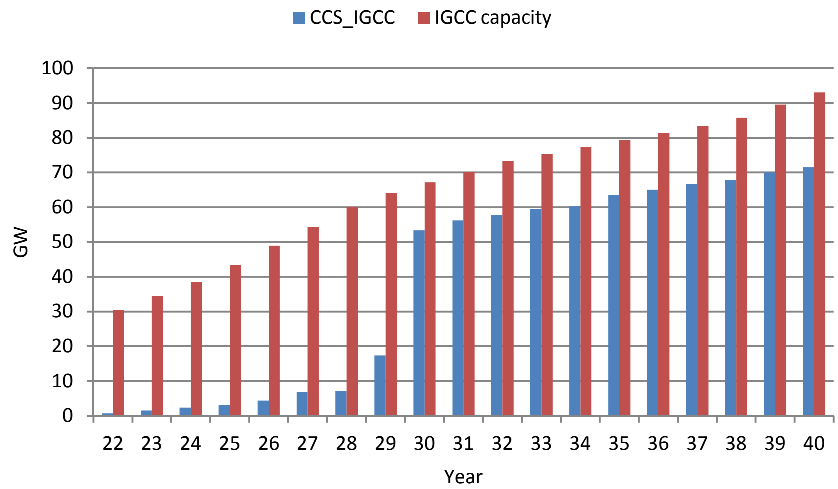

Figure 6-6.Capacity of IGCC with CCS VS capacity of IGCC in Sce4

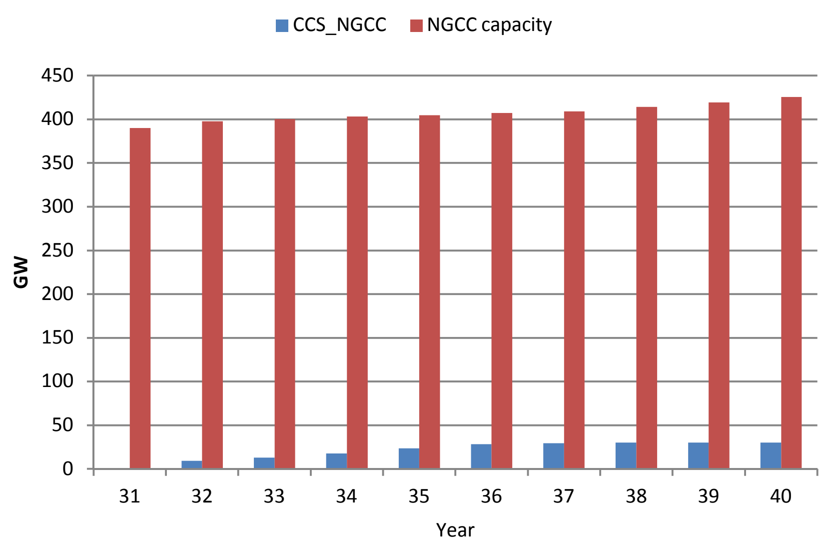

Figure 6-7. Capacity of NGCC with CCS VS capacity of NGCC in Sce3

6.3 Sensitivity Analysis

Sensitivity analysis was used to study how output changes in response to variation in input data. By performing sensitivity analysis we could find particular sensitivity factors that significantly affect the model output. Good execution of sensitivity analysis will help to apply the model wisely when faced with variation and uncertainty. Generally speaking, the most sensitive factors in a resource-planning model usually include electrical demand, peak load forecast, fuel cost, and retirement assumptions. In this study, since the principal focus of the research is on fossil fuel power-plant and renewable resource development, sensitivity factors having impact on these issues were selected.

Decrease investment costs of solar generation technologies

Although wind technology is competitive with traditional fossil fuel technologies, solar technology seems too expensive at this time to warrant further development. It is expected that the cost of solar technology will decrease in the future. A preliminary study on decreasing the investment cost of solar technologies shows how the investment in solar capacity would change in response to cost reduction. Figure 6-8 shows solar beginning to seem practical to develop when PV solar is less than $3367 /KW and the solar thermal price is less than $2828/KW.

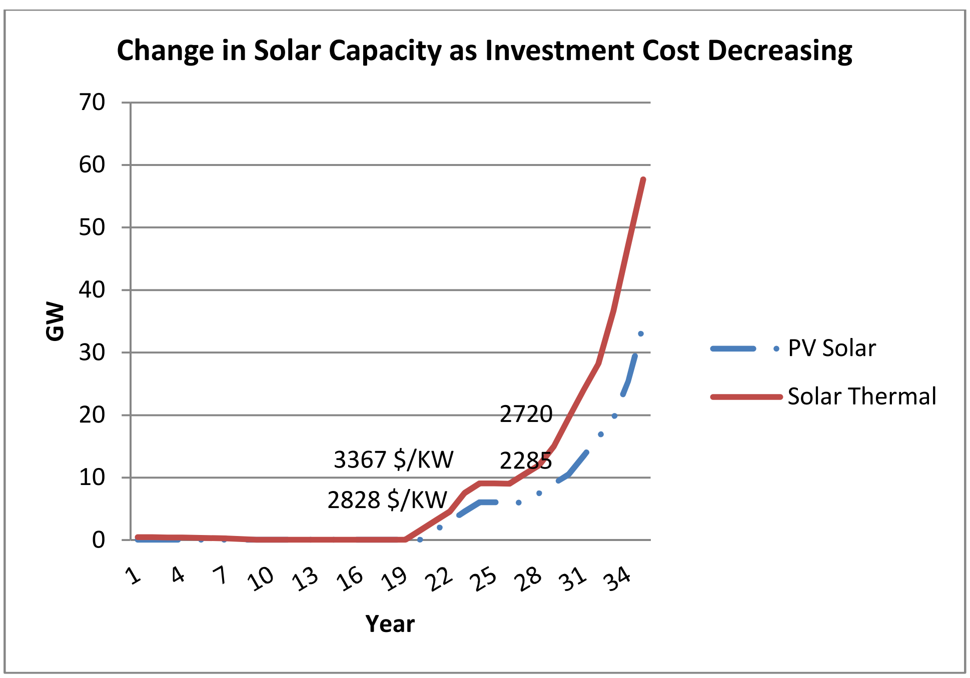

Figure 6-8. Changes in solar capacity as investment cost decreasing

Increase maximum investment limitation each year

NETPLAN is designed to meet electricity demand and reliability requirements at minimum cost. Investment in the most economically-attractive technology will occur until it reaches the maximum-investment limitation, so, this limitation is an important factor affecting the generation portfolio. Only the natural gas maximum-investment limitation variation was performed in this study, it would also be important to conduct sensitivity analysis in response to changes in maximum-investment limitations of other generation technologies. For example, the maximum investment capacity of wind in each NERC region might be different due to difference in available area in each NERC region.

Figures 6-9 through6-10 show the difference of natural gas capacity due to differences in maximum-investment limitation. When the max investment cap is set to 1.25 GW/year for each region, there is a significant decrease after year 25 because many natural gas power plants are retired and new investment is curbed. After the maximum-investment cap is changed to 2GW/year, there are more capacities available, so the total capacity of natural gas power plants increases after year 25.

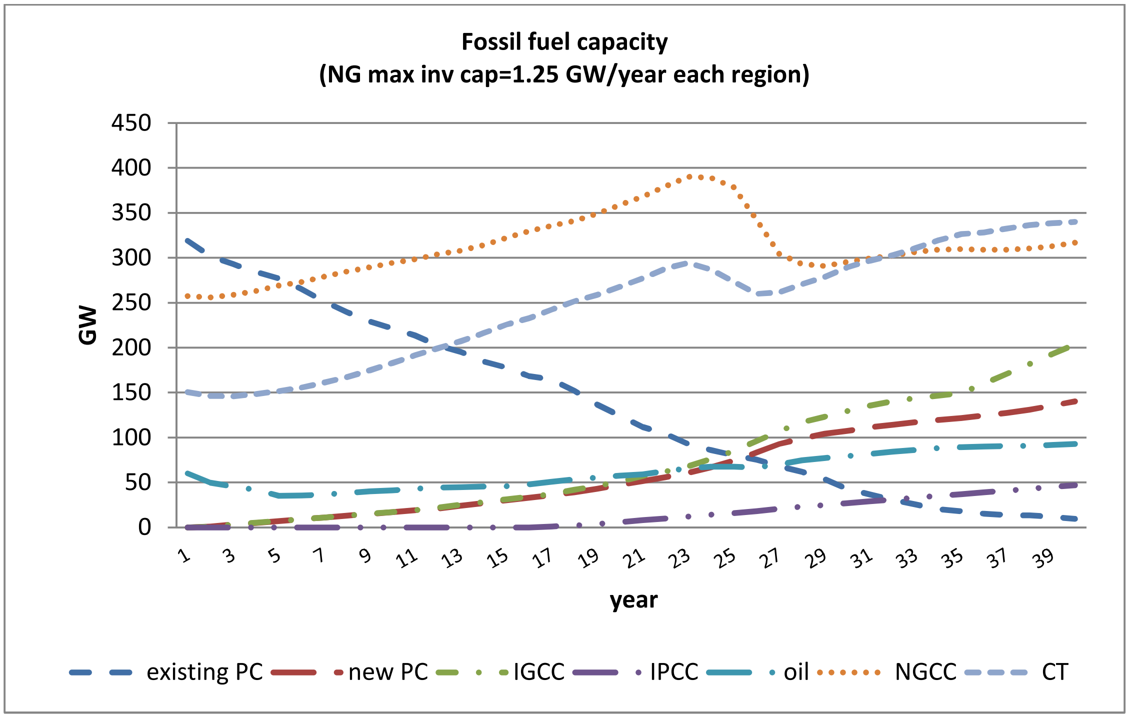

Figure 6-9. Fossil fuel capacity when natural gas investment limit is 1.25 GW/year

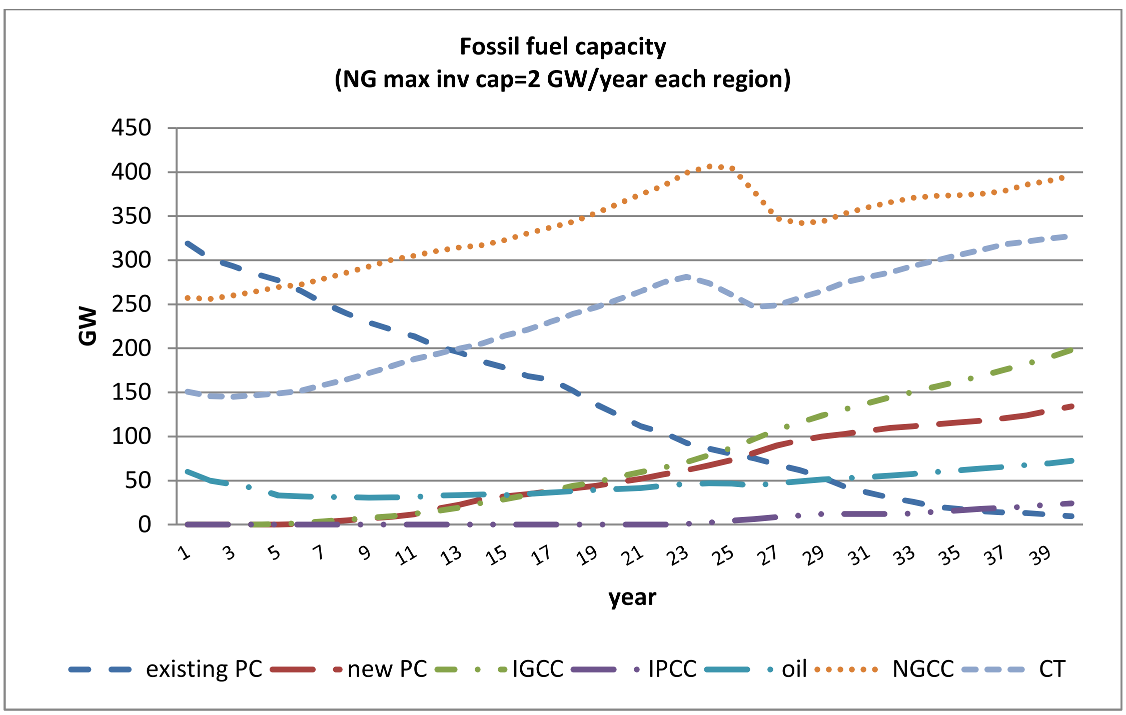

Figure 6-10. Fossil fuel capacity when natural gas investment limit is 2 GW/year

Carbon tax set by 20, 30, and $50/Ton

The studies were performed by setting the carbon tax at $20/Ton, $30/Ton, and $50/Ton. Unlike the case when carbon tax is$50/Ton, when it is $20/Ton or $30/Ton, no CCS is installed. However, as shown in Table 6-14, the proportion of fossil-fuel power plants decreases in all cases. Figure 6-11 shows the differences of CO_2 emission among the three cases.

Table 6-14.The percentage of fossil fuel capacity

	y1	y10	y20	y30	y40
Sce2	77.9%	72.1%	70.1%	71.0%	71.7%
Carbon tax 20	77.9%	69.9%	66.4%	66.3%	69.1%
Carbon tax 30	77.9%	68.5%	64.4%	64.0%	67.2%
Carbon tax 50	77.9%	67.6%	63.7%	63.5%	65.2%

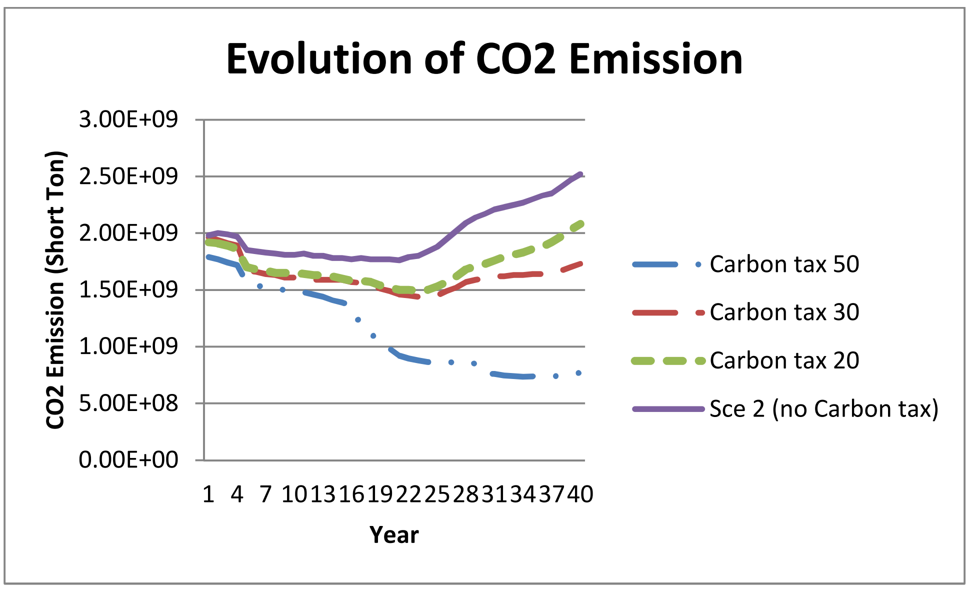

Figure 6-11. Evolution of CO_2emission

Natural gas price decreases

When the natural gas price decreases by $1.5/MMBtu, total cost deceases by 13%. There is a slight increase in the proportion of fossil-fuel power plants and decrease in that of renewable power plants. Figure 6-12 shows the increase in the natural gas capacity over 40 planning years.

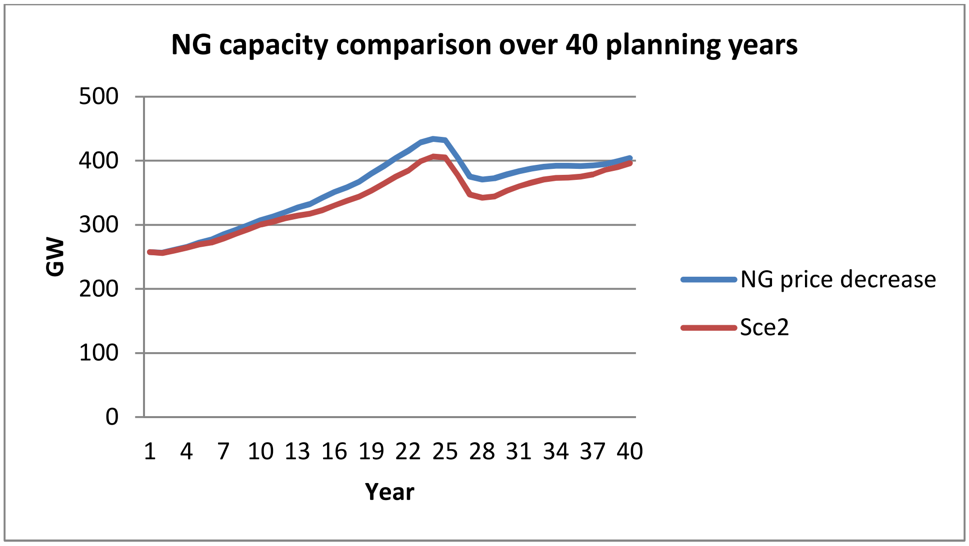

Figure 6-12.Natural gas capacity comparison over 40 Planning years under

The sensitivity analysis shows that investment cost of renewable technology, maximum capacity investment per year, compliance cost, and fuel price will change the generation portfolio output. Among these sensitivity factors, investment cost and maximum capacity has the greatest impact on the output of the generation portfolio. This is due to NETPLAN first investing in the most economical generation technology, followed by investment in the next most economical generation technology after reaching the limitation of less expensive technology.

6.4 Result Comparison

In this part, the NETPLAN Installed Capacity by resources is compared to the ReEDS base-case result and the NETPLAN generation by resources is compared to the NEMS base-case result. The NETPLAN effect of earlier retirement of coal power plants due to MACT is compared with that of the NERC 2010 reliability study. The NETPLAN Sce2 result is used since both ReEDS and NEMS (EIA) account for emission caps and retrofitting coal power plants.

The following observations result from comparing NETPLAN installed capacity by source (Figure 6-13) with installed-capacity build out in ReEDS (Figure 6-14).

1. Both ReEDS and NEPLAN installed capacity gradually shift to low-carbon options and the proportion of renewables and natural gas capacity increases.

2. NG installed capacity has a clear tendency to increase in both study cases. In 2050, the total NG installed capacity accounts for about 1/3 of the total installed capacity.

3. Coal installed capacity increases slightly after 2030. Since the total capacity increases from about 1000 GW to 1400 GW or above, the proportion of coal capacity decreases.

4. NETPLAN has more wind capacity invested than does ReEDS. Possible reasons include:

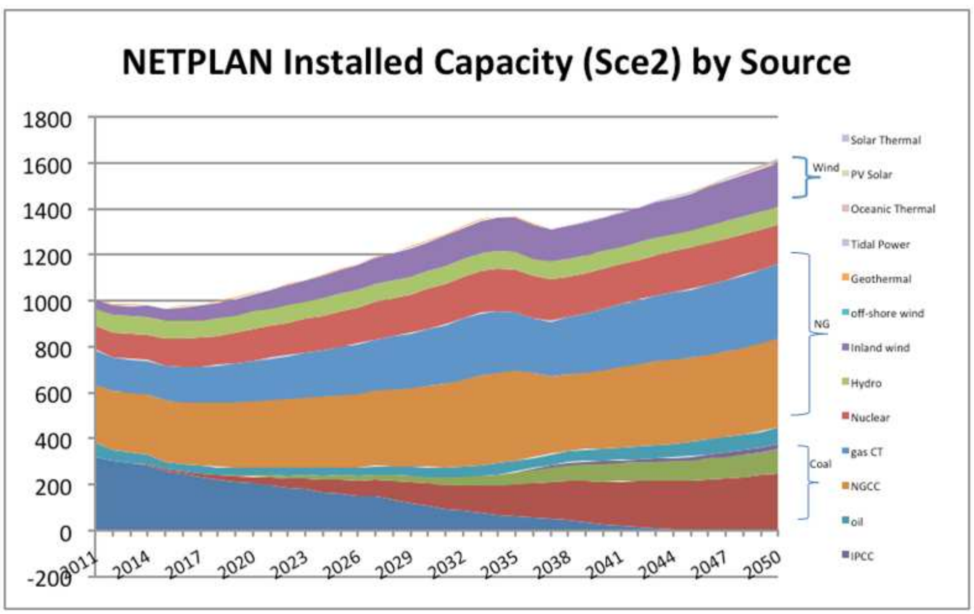

Figure 6-13.NETPLAN installed capacity by source 2011-2050

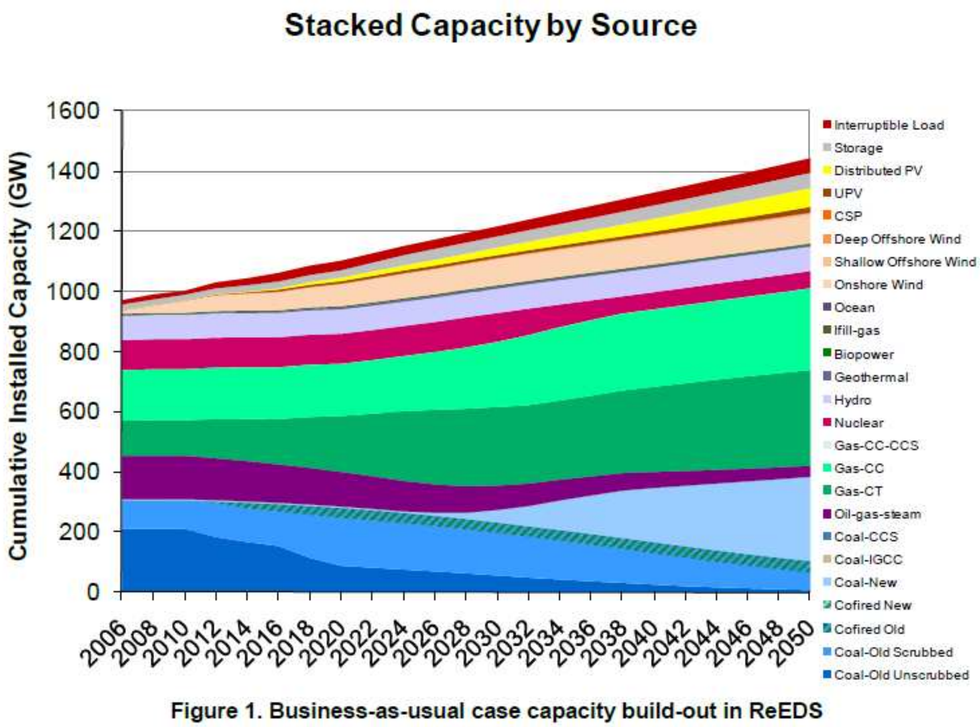

Figure 6-14.ReEDS installed capacity by source 2006-2050[6]

-Maximum investment capacity may be over-specified in some regions.

-No operating-reserve constraints to account for wind-power impact have been used in this study.

5. Other observations include:

-NETPLAN has more installed nuclear capacity than the ReEDS result. Possible reasons for this are low investment cost, high maximum capability specified in regions, and no constraint on nuclear serving base load.

-NETPLAN has fewer solar PV due to high investment cost and no Renewable Standard Portfolio constraints.

-NETPLAN doesn’t model storage and disrupted load.

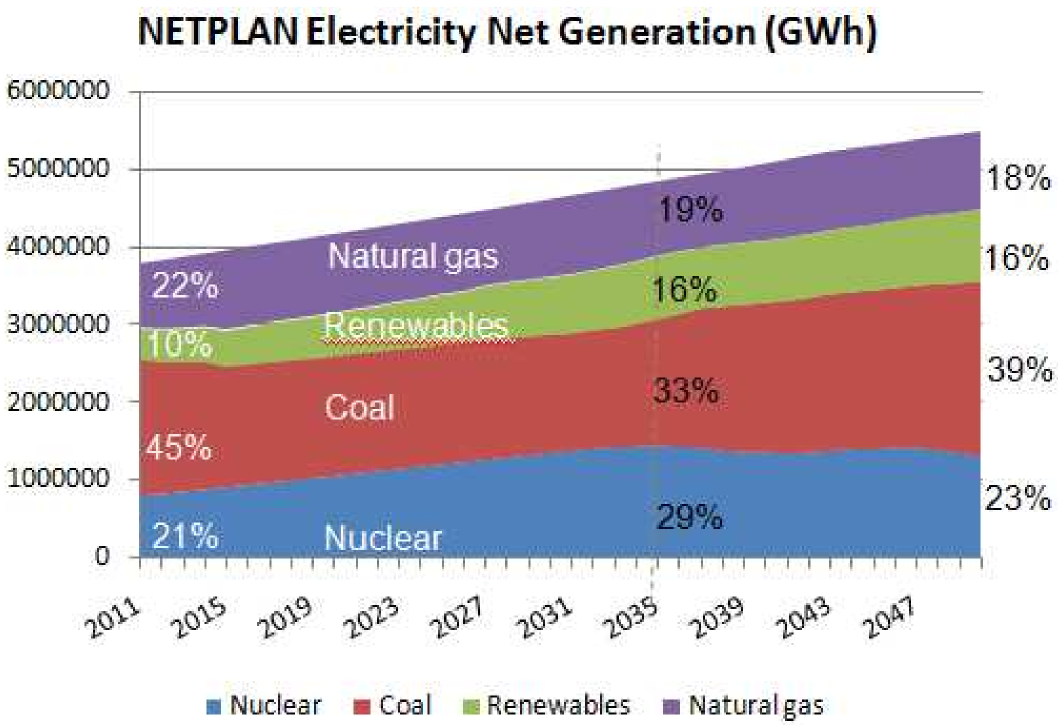

Figure 6-15.NETPLAN electricity net generation by source 2011-2050

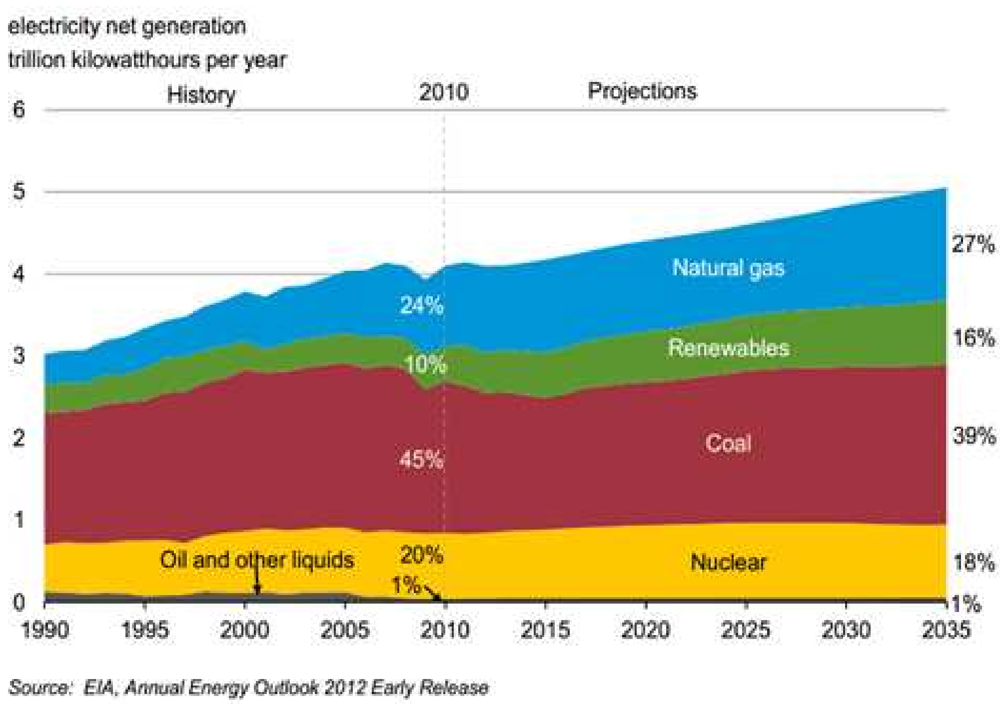

Figure 6-16. NEMS Electricity Net Generation by source 1990-2035 Error! Reference source not found.**[48]**

The following observations result from comparing NETPLAN net generation by source (Figure 6-15) with net generation in NEMS (Figure 6-16).

1. EIA generation by resource shows that net electrical generation from renewables and natural gas increases.

2. NETPLAN exhibits the same trend as NEMS for both coal and renewable resources, i.e., coal generation decreases and renewable generation increases.

3. NEPLAN includes more generation from nuclear resources. This result is consistent with installed-capacity comparison of NEPLAN with ReEDS that shows that NETPLAN invests in more nuclear capacity.

4. NEPLAN has less NG generation, possibly because of

-High NG price assumption.

-No start up and shut down constraints for non-cycling units.

For the above reasons, generation from resources with low operational costs meets the peak-hour demand, so part of NG CC and all the NG CT units are used for reserve because of high operational costs.

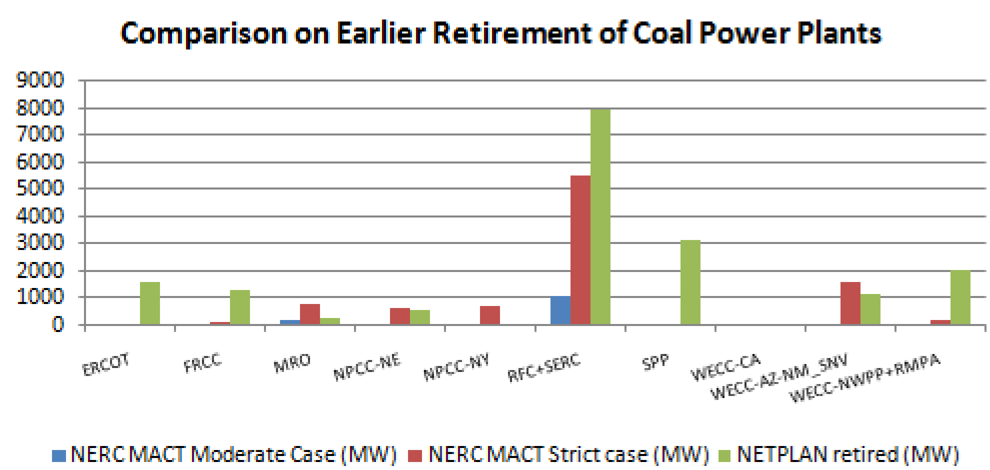

Figure 6-16.Comparison on earlier retirement of coal power plants

In Figure 6-17, NETPLAN earlier retirement of coal power plants is compared with NERC moderate and strict cases [33]. The total capacity of retired power plants due to implementation of MACT in the NERC report is 14.8GW. The total NETPLAN earlier-retired capacity is 18.3 GW.

It is noted that NETPLAN uses old NERC regions, while the NERC report uses new NERC regions. These two results do not match very well in the MRO, SERC, and RFC regions, since old NERC region MAIN is shared by new NERC regions RFC, SERC, and MRO. Therefore, RFC and SERC are combined to make the two results comparable. This shows that RFC and SERC are the two regions with the largest retired capacity (Figure 6-18).

The comparison shows that NEPLAN has more retired capacity in the ERCOT, FRCC, SPP, and WECC-NWPP-RMPA regions. One possible explanation for this is that NETPLAN existing coal capacity is 25 GW higher than indicated in the NERC reports. Although retirement before 2015 has been introduced in NETPLAN, it is highly possible that in 2015there is actually older coal capacity existing in these regions, leading to higher retirement capacity in the NETPLAN result.

Figure 6-17. Total US coal fired capacity Error! Reference source not found.**[36]**

CHAPTER 7: CONCLUSIONS

7.1 Contributions

This research makes principal contributions:

Identify the uniqueness of NETPLAN: NETPLAN has been assessed by making model comparisons with NEMS (DOE) and ReEDs (NREL). NEMS is one of the two existing planning tools representing the multiple sectors energy and transportation. ReEDs has been developed to integrate renewable energy, especially wind energy, into power-system resource and transmission planning. Comparisons among the three models include model design, solution approach, objective and constraints in LP, and elements in energy and transportation systems. NETPLAN is assessed as an effective new tool for power-system planning because of its uniqueness in multi-sector, multi-objective design.

Extension of NETPLAN software: a new design accounting for decision-making for coal power plants under EPA-imposed rules has been applied. The multi-level, multi-arc design allows power plants to install emission control equipment, such as FGD, SCR and CCS, to meet EPA regulations at minimum cost. Since installation of emission-control equipment has impact on the characteristics of power plants, including increasing their operational cost, decreasing their efficiency, and decreasing their maximum capacity. The new design can account for these impacts by adding additional operation costs and lost energy along the arcs, and adding negative contribution to the peak load.

7.2 Conclusions

In the first half, NETPLAN is assessed by making model comparisons with NEMS (DOE) and ReEDS (NREL). Based on this model comparison, the strengths and weaknesses of NETPLAN are discussed, yielding the following conclusions.

1. NETPLAN is unique in providing combined investment planning for energy systems and transportation systems. NEMS and NETPLAN both represent multiple sectors, but NEMS is different in that is an equilibrium model aiming to balance energy demand and energy supply. Although NEMS may yield an optimal solution in individual sectors (electric sector and petroleum sector), it does not provide an overall optimal solution for multi-sectors. In contrast, NETPLAN is an optimal model that integrates multi-sectors into one model. As a result, NETPLAN is able to provide a single optimal solution for multi-sector investment planning.

2. NETPLAN is an effective tool for meeting the latest requirements of today's power-system planning. It incorporates wind variability, emissions from both electric and transportation sectors, electrification of transportation, and uncertainty. It is also a multi-objective model providing tradeoffs among minimum cost, sustainability, and resilience.

3. The arc-and-node structure used in NETPLAN makes it more capable than traditional planning models. There are several advantages of applying such an arc-and-node structure. First, the physical meaning of the model is easy to understand. Second, both capacity and generation flows are variables, allowing NETPLAN to simultaneously perform both investment planning and simulation of production cost. Third, the arc and-node structure is friendly to incorporation of transmission lines, so NETPLAN is able to incorporate DC

power flows as transmission constraints. Transmission-line planning and generation-expansion planning are integrated into one model.

In the second half of the thesis, NETPLAN is applied to analysis of proposed environmental regulation impact. Study scenarios for examining the impact of existing and proposed environmental regulations were developed, yielding the following conclusions.

1. A requirement for installing FGD and SCR increases both investment cost and operational cost of coal power plants, making them less competitive with other generation technologies like natural gas and wind. However, the total proportion of fossil fuel power plants does not significantly decrease as the investment of natural gas power plants increases.
2. Compliance strategies could significantly reduce emissions of SO_2 and NO_X from coal power plants. Therefore, the new emission caps on SO_2 and NO_X have little influence on the generation portfolio when compared to existing emission caps. However, stricter emission caps will increase both the total investment and the operational cost.
3. The requirement of adding a carbon tax further promotes the investment into wind capacity while the proportion of fossil fuel power plants is further decreased. CCS will not be installed until the carbon tax is high enough.
4. Wind capacity should first be invested in those regions with plentiful wind resources, even though there is a clear tendency toward wind investment increase in regions with fewer wind resources when environmental regulations become stricter.
5. Sensitivity analysis shows that investment cost of renewable technology, maximum capacity investment per year, compliance cost, and fuel price will change the generation portfolio output. Among these sensitivity factors, investment cost and maximum capacity

has the greatest impact on the output of generation portfolios due to NETPLAN choosing to invest first in the most economical generation technology. Investment in the next most economical generation technology occurs when the limitations of less expensive technology are reached.

APPENDIX A. NOMENCLATURE

A. Decision Variables

$e_{(i,j)}(t)$: Operational flow of energy arc from node i to node j, for time step t (MWh);

$ud_j^E(t)$: unserved demand at electric system node i, for time step t (MWh);

$eCap_{(i,j)}(t)$: Capacity investment on energy arc from node i to node j, for time step t (MWh)(t);

$rm_j^E(t)$: Reserve margin for node j in electric system;

$\theta_i(t)$: Phase angle at node i, used to model DC power flow (radians);

$f_{(i,j,k,m)}(t)$: Operational flow of transportation arc from node i to node jfor commodity k using transportation mode m during time step t (ton);

$infInv_{(i,j,l)}(t)$: Infrastructure l capacity investment for transportation arc from node i to node j for time step t (ton/hour);

B. Sets and network

N^E: Set of energy Node;

$N_d^E \subset N^E$: Subset of energy nodes where demand equations are enforced

$N_p^E \subset N^E$: Subset of energy nodes where peak demand equations are enforced

A^E: Set of energy arc

A_{DC}^E: Set of energy arc

C. Parameters

$\eta_{(i,j)}(t)$: Efficiency of arc (i, j) during time (unitless);

$d_j^E(t)$: Electricity demand at node j in electric system, during time t (MWh)

$d_j^{ET}(t)$: Electricity demand at node j due to the demand of transportation, during time t (MWh)

$cc_{(i,j)}(t)$: Capacity credit for power plants arc (i, j), during time t (unitless);

$peakD_j^E(t)$: Peak load at node j in electric system, during time t; (MW)

$b_{(i,j)}(t)$: Impedance elements in DC power flow equation, during time t (unit);

$n^{E}_{(i,k)}$:The node in energy system with location i for energy commodity k;

heatcontent_k: The heat content of energy commodity k enables the conversion of different kind of energy, for example, from coal to electricity.

$ErSO2_i$ and $ErNOX_i$: SO_2 and NO_X emission rate for per MWh energy flow through the fossil fuel power plant arcs.

α_i and β_i: Emission reduction rate due to the installation of SO_2 and NO_X emission control equipment.

D. Time Variables

$\Delta(t)$: Length of time step t (h);

t : Time instance in the simulation domain;

T: The time period that the emission cap is applied to. It could be one year or ozone month.

APPENDIX B. DATA FILES USED IN CASE STUDIES

Appendix B describes the data files used in the case studies in this thesis. Adding environmental regulations and emission controls require adding more data in several input files. The input data covers the unit characteristic of capacity credit, capacity factor, investment cost, operation cost, and maximum operation capacity. The corresponding files and new addition data are described blow.

arcs_List.csv and **nodes_List.csv**

All new arcs are in arcs_List.csv. All new nodes should be added in nodes_List.csv. The nodes and arcs for pulverized coal (existing and new), IGCC and NGCC is illustrated in FiguresB-1, B-2, and B-3.

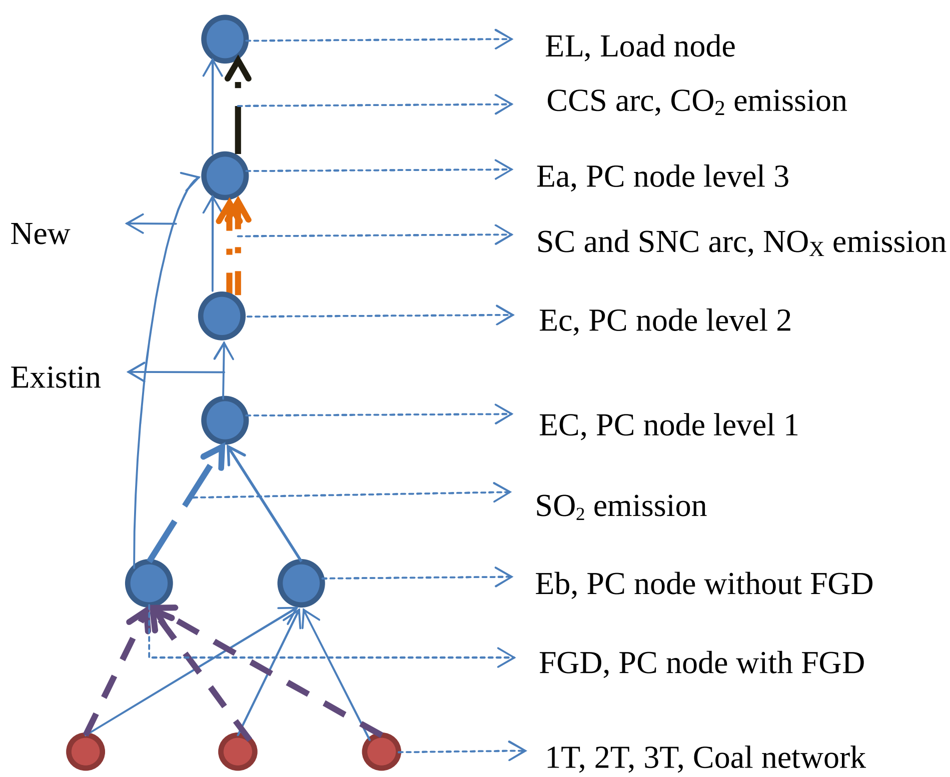

Figure B- 1. Arcs and nodes structure designed for PC

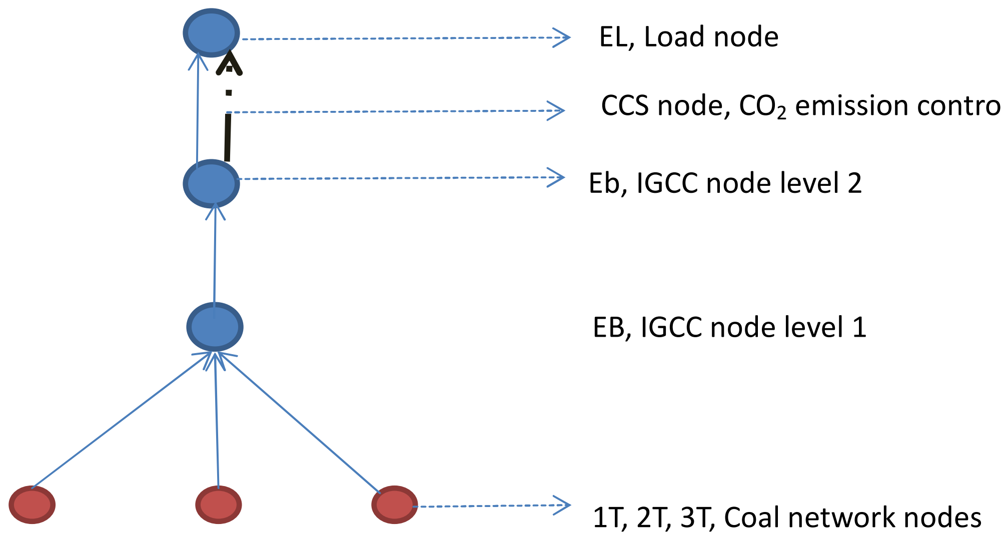

Figure B- 2. Arcs and nodes structure designed for IGCC

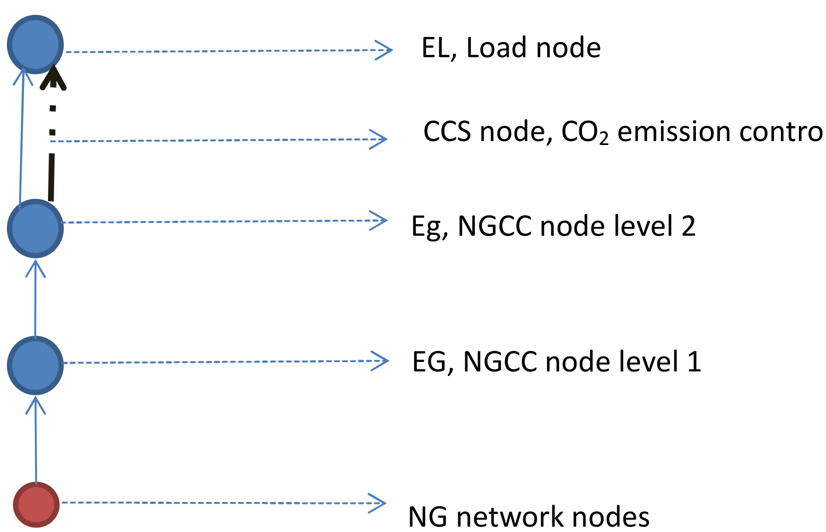

Figure B- 3.Arcs and nodes structure designed for NGCC

Parameters.csv

In this file, the following items are added to expand the sustainability metrics. There are two measurement of NO_X. $EmNO_X$ is used to measure the total NO_X emission at the national level. $Em2NO_X$ is used to measure the NO_X emission in regions covered by NO_X SIP Call trading program.

AddMetric	$EmNO_X$
AddMetric	$Em2NO_X$
AddMetric	EmSOx

sust_Limits.csv

This file is used to add emission caps at national level or regional level. Proposed emission cap is added in planning year 5. When % is use, the emission caps in the low are inactivated.

code	y1	y2	y3	y4	y5	Unit
$EmCO_2$	1.70E+09	1.67E+09	1.63E+09	1.60E+09	1.56E+09	Ton
$Em2NO_X$	527500	527500	527500	527500	527500	Ton
%EmSOx	9944444	9944444	9944444	9944444	9944444	ShortTon
EmSOx	9944444	9944444	9944444	9944444	3323422	Short Ton
$EmNO_X$	9944444	9944444	9944444	9944444	2087815	Short Ton

arcs_OpEmSOx.csv, arcs_OpEmNO_X.csv, and arcs_OpEmCO_2.csv

The emission rate for different type of fossil fuel power plants are described in files arcs_OpEmSOx.csv, arcs_OpEmNO_X.csv, and arcs_OpEmCO_2.csv. An example of SO_2 emission is given here.

from	To	Constant short ton/K-short-Ton	
1T	Eb	18.72	Emission rate for PC without FGD using coal type 1T
2T	Eb	30.12	Emission rate for PC without FGD using coal type 2T
3T	Eb	12.02	Emission rate for PC without FGD using coal type 3T
4T	Eb	6.87	Emission rate for PC without FGD using coal type 4T
1T	FG	1.40	Emission rate for PC with FGD using coal type 1T
2T	FG	2.26	Emission rate for PC with FGD using coal type 2T
3T	FG	0.90	Emission rate for PC with FGD using coal type 3T
4T	FG	0.52	Emission rate for PC with FGD using coal type 4T
1T	ED	1.40	Emission rate for IGCC using coal type 1T
2T	ED	2.26	Emission rate for IGCC using coal type 2T
3T	ED	0.90	Emission rate for IGCC using coal type 3T
4T	ED	0.52	Emission rate for IGCC using coal type 4T

From	To		
EO	EL	21.08	Emission rate for Oil

arcs_CapacityFactor.csv

This file is used to describe the contributions of power plants to the peak load. The following parameters are added to represent the impact of emission controls to the peak load.

From	To	Constant	
Ec	CC	-0.1	Negative contribution of Coal power plants with CCS to peak load
Ec	SC	-0.01	Negative contribution of Coal power plants with SCR to peak load
Ec	SN	-0.01	Negative contribution of Coal power plants with SNCR to peak load
FG	EC	-0.01	Negative contribution of Coal power plants with FGD to peak load
Ed	CC	-0.1	Negative contribution of IGCC with CCS to peak load
Ef	CC	-0.1	Negative contribution of natural gas power plants with CCS to peak load

arcs_Cf.csv

This is a new file added when LDC is not used. The purpose is to use capacity factor to limit the generation from non-intermittent power plants. The parameter input is the reciprocal of average capacity factor. Without this file, the generation from non-intermittent power plants, such as nuclear, hydro, and coal, will be the capacity multiplied by 8760 hours each year. As a result, generation from low operation cost power plants, such as nuclear, hydro, and coal, will increase. Generation from high operation cost power plants, such as NGCC and CT will decrease.

From	To	Constant	Capacity factor	Arc type
EC	Ec	1.428571	0.7	Existing Coal Power Plant
FG	EC	1.428571	0.7	Existing Coal Power Plant With FGD
Eb	EC	1.428571	0.7	Existing Coal Power Plant Without FGD
FG	Ea	1.25	0.8	New Pulverized Coal
ED	Ed	1.25	0.8	New IGCC
EN	EL	1.11	0.9	Nuclear
EO	EL	11.111	0.1	Oil
EH	EL	2.5	0.4	Hydro
EG	Eg	1.25	0.8	NGCC
ET	EL	1.25	0.8	CT
E1	EL	1.11	0.9	Geothermal

arcs_Eff.csv

This file is used for two purposes. One is to describe the energy conversion between fuel systems and electric systems. The other is to describe the energy loss along the power plant arcs. The physical meaning of each parameter is given below.

From	To	Constant (GWh/thousand short ton)	
1T	Eb	1.10	Heat rate for existing coal power plants without FGD using coal type 1T
2T	Eb	2.07	Heat rate for existing coal power plants without FGD using coal type 2T
3T	Eb	1.95	Heat rate for existing coal power plants without FGD using coal type 3T
4T	Eb	1.48	Heat rate for existing coal power plants without FGD using coal type 4T
1T	FG	1.92	Heat rate for existing coal power plants with FGD using coal type 1T
2T	FG	2.62	Heat rate for existing coal power plants with FGD using coal type 2T
3T	FG	2.14	Heat rate for existing coal power plants with FGD using coal type 3T
4T	FG	2.18	Heat rate for existing coal power plants with FGD using coal type 4T

From	To	Constant	
Ec	SC	0.99	Heat rate penalty due to the installation of SCR for existing coal power plants
Ec	SN	0.99	heat rate penalty due to the installation of SNCR for existing coal power plants
Ea	CC	0.67	Heat rate penalty due to the installation of CCS for pulverized coal power plants
Ed	CC	0.67	Heat rate penalty due to the installation of CCS for IGCC
Ef	CC	0.67	Heat rate penalty due to the installation of SCR

arcs_InvCost.csv

This file is used to input the parameters of new investment. Since the pulverized coal is classified into existing PC and new PC, there is no investment cost on the arcs which represents the existing PC. In order to represent the variance in the investment cost over the planning horizon,y1, y2, and so on are needed to add in the first row. The corresponding investment cost is filled out in the intersection between the column of year and the row representing arc type.

From	To	Constant(million $/GW)	y1	y2	Arc type
Ea	CC	1932			Pulverized coal with CCS
Ec	SC	400			Existing power plants with SCR
Ec	SN	75			Excising power plants with SNCR
FG	EC	420			Existing power plants with FGD
FG	Ea	3767			New pulverized coal
%EC	Ec	2967			% represents no investment cost in existing coal power plants
ED	Ed	4545.8			IGCC
Ed	CC	1783			IGCC with CCS
Ef	CC	1057			NGCC with CCS
EG	Eg	978			NGCC
EV	E	7210.3	6994.0	6784.2	Solar
EU	E	6056.9	5875.2	5698.9	Solar

arcs_InvMax.csv

There is no limitation of the investment capacity for emission controls. Therefore, no new input is added in this file.

arcs_LifeSpan.csv

It is assumed that all the emission controls, once installed, will last until the existing power plants retire. The life span of the emission control is set to the upper limitation. The generation flow along the emission control arc is limited by the arc representing maximum operation capacity.

From	To	Constant	Emission control type
Ec	SC	y40	SCR for existing coal power plants
FG	EC	y40	FGD for existing coal power plants
Ea	CC	y40	CCS for pulverized coal
Ed	CC	y40	CCS for IGCC
Ef	CC	y30	CCS for NGCC

arcs_OpCost.csv

This file is used to describe the additional operation cost due to the operation of emission control equipment and carbon tax. The operation cost for new PC and IGCC are obtained by adding operation cost of FGD and SCR on the original operation cost.

From	To	Constant (million $ / GWh)	
Ea	CC	0.00500	Operation cost due to CCS on PC
Ec	SC	0.00300	Operation cost due to SCR on existing PC
Ec	SN	0.00230	Operation cost due to SNCR on existing PC
FG	EC	0.00300	Operation cost due to FGD on existing PC
FG	Ea	0.00840	Operation cost of new PC
ED	Ed	0.00816	Operation cost of new IGCC
Ed	CC	0.00500	Operation cost due to CCS on IGCC
Ef	CC	0.00300	Operation cost due to CCS on NGCC
Ea	EL	0.04137	Carbon tax on PC without CCS
Ea	CC	0.00621	Carbon tax on PC with CCS
Ed	EL	0.03893	Carbon tax on IGCC without CCS
Ed	CC	0.00584	Carbon tax on IGCC with CCS
Ef	EL	0.01832	Carbon tax on NGCC without CCS
Ef	CC	0.00275	Carbon tax on NGCC with CCS
ET	EL	0.02501	Carbon tax on CT
EO	EL	0.03636	Carbon tax on Oil

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