

INFRASTRUCTURE PLANNING AND OPERATIONAL SCHEDULING FOR POWER GENERATING SYSTEMS: AN ENERGY-WATER NEXUS APPROACH

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Abstract

Due to population growth and economic prosperity, the demand for energy and potable water is rapidly increasing around the world. As the demand for energy and water increases, the need of decision-making strategies for power generating systems that exploit the Energy-Water Nexus (EW-N) is becoming more apparent. These decision-making strategies are complex and comprise of decisions related to: (i) the construction of new power plants and energy storage devices; (ii) the conversion of cooling technologies for existing power plants; and (iii) environmental impacts. Since the type of generating and cooling technology of a power plant directly affects its water usage, the decision-making strategies are intrinsically multi-objective. Therefore, a decision-making framework based upon the aforementioned concerns is essential for developing a power generating system that is able to meet the energy demands and sustainably utilize water. In this work, we present a novel EW-N superstructure-based representation and multi-objective optimization framework for infrastructure planning and operational scheduling of power generating systems with renewable generators and large-scale energy storage devices. The EW-N problem is posed as a two-stage stochastic mixed-integer linear program that minimizes the capital expenditures, operational cost, and water usage of the system. The model includes planning decisions such as the ability to construct additional power plants, storage units, and convert the cooling technologies of existing power plants. The model also includes scheduling decisions which determine how much power each plant generates, how energy is allocated within the system, and when energy is stored and released from storage devices. The model is implemented into a case study within the Edwards Aquifer region of Texas for a centralized power generating utility and determines the optimal conversion, expansion and operational decisions for the utility given the current infrastructure of the system.

Keywords

Two-Stage Stochastic Programming, Planning and Scheduling, Energy-Water Nexus

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Introduction

The Energy-Water Nexus (EW-N) has recently become a new focus of research within the Process Systems Engineering community (Avraamidou et al., 2018) (Nie et al., 2019). The relationships between these two elements of society are deeply interconnected. For instance, 15% of global water use is allocated towards energy and 8% of global energy use is allocated towards water (García and You, 2016).

In recent years renewable power generators (wind and solar PV farms) have gained increased penetration within the market, both of which do not utilize water for energy production. For instance, the Electric Reliability Council of Texas (ERCOT), which manages the flow of power within the majority Texas, reports that 22% and 1% of its generation capacity in 2017 comes from wind farms and solar farms respectively (Energy Reliability Council of Texas, 2018b). Due to the increased penetration of renewable generators in the market, there is a need to alleviate the stresses brought on by their intrinsic intermittent nature. Large-scale energy storage devices have been proposed to capture and store energy, when there is an excess supply of energy or when energy prices are low, to be utilized at a later time (Zakeri and Syri, 2015).

In 2017 70% of the generation capacity of ERCOT was natural gas or coal fired power plants, both of which consume cooling water for their steam cycle (ERCOT, 2018). Three predominant cooling technologies utilized in power plants “once-through”, “wet cooling”, and “dry cooling” systems (Stillwell et al, 2011). It been proposed to retrofit the cooling technologies of existing power plants that utilize “once-through” systems to either “wet-cooling” or “dry cooling” systems to reduce the amount of cooling water that these power plants consume (Loew et al., 2016).

The goal of this work is to put forth a superstructure representation and two-stage stochastic mixed-integer optimization framework for infrastructure planning and operational scheduling of a power generating systems based upon EW-N connections. The presented superstructure allows for expansion of the current infrastructure, conversion of existing generators to reduce the amount of cooling water utilized, and the addition of large-scale energy storage devices as well as the day-to-day operational scheduling of the system. The goal of the aforementioned multi-objective framework is to reduce the capital cost, operational cost and water usage of the power generating system, while ensuring that the demand of energy from consumers is met.

The framework is illustrated through the use of a case study for a power generating utility operating in the Edwards Aquifer region of Texas. The Edwards Aquifer region of Texas was chosen as the case study because it is an extremely water stressed region undergoing population rapid population growth due to the fact that San Antonio, TX, is a growing metropolitan hub (McCarl et al., 2018) and (Daher et al., 2019).

This article is organized as follows. First in Section 2, the EW-N infrastructure planning and operational scheduling problem for a power generating system is presented. In Section 3, the optimization model of the EW-N planning and scheduling problem is presented. In section 4, the case of a power generating utility operating in the Edwards Aquifer is presented. In Section 5, the results of the case study are presented and discussed. In Section 6, the concluding remarks are given.

EW-N Planning and Scheduling Problem

The objective of the EW-N problem is to determine the optimal infrastructure expansion and operational decisions for a power generating utility operating in the Edwards Aquifer so that the capital cost, operational cost and water usage of the system is minimized, while at the same time ensuring the energy demands are met in each of the regions it operates in.

The planning horizon, $\mathcal{P}$, is 20 years with 5-year time discretization and is uncertain with respect to energy demand. The scheduling problem for each planning period, is broken down into a set of representative weeks, $\mathcal{S}_2$. The scheduling horizon, $\mathcal{H}$, for each of these weeks is divided into 1-hour time discretization. For each representative week there is a solar irradiance, wind, and demand profile for each of the regions that the utility operates in.

Without loss of generality, we are given a set, $\mathcal{G}_1$, of existing power plants owned and operated by the utility company as well as their respective cooling technologies for the applicable plants. The utility also has the ability to purchase additional renewable and nonrenewable power plants as well as energy storage devices, which are denoted by the sets $\mathcal{G}_3$ and $\mathcal{B}$ respectively. There is also a set, $\mathcal{G}_2$, of potentially converted power plants who have had their cooling technologies upgraded from a “once-through” system to a “wet-cooling” system. It is to be highlighted that it is assumed that “dry-cooling” systems are not applicable in this region due to the extremely hot and dry summers that are typical of this part of Texas.

The capital cost, operational cost, and operational parameters are given for each power plant and storage device. The utility also has the ability to purchase additional power from other utilities if it does not have the generation capacity to meet its demands.

Algebraic Model

The optimization model is posed as a two-stage multi-period stochastic mixed-integer linear program with two competing objectives. The first objective is to minimize the capital and operational cost of the system and the second objective is to minimize the water usage of the system. The uncertainty in the problem is respect to the growth in energy demand over the course of the planning horizon.

There are planning constraints that allow for the construction of new power plants and new storage units as

well as the conversion of the cooling technologies of existing power plants. There are scheduling constraints that ensure each region meets its energy demand and does not utilize more water than it has been allocated. There are additional scheduling constraints for the operation of storage devices and power plants (Lara et al., 2018) (Gabielli et al., 2018) (Zang et al., 2018). It is assumed that these storage devices have generators to charge the device and to convert the stored energy back into electric power. There are also nonanticipatory constraints, which ensure the planning decisions that occur in the first period of the planning problem are identical for all scenarios.

The capital cost, operational fixed cost, operational variable cost parameters are weighted to bring their cost to the present value as well as scaled as a function of their representative weeks.

Objective Function

The capital cost to construct additional power plants and energy storage devices is given by Eq. (1).

$$J_1 = \sum_{n \in \mathcal{G}_3 \cup \mathcal{B}} \sum_{p \in \mathcal{P}} \sum_{s \in \mathcal{S}_1} FC_{n,p,s}^{\text{build}} \cdot y_{n,p,s}^{\text{build}} \quad (1)$$

The capital cost to upgrade the cooling technologies of existing power plants is given by Eq. (2).

$$J_2 = \sum_{g \in \mathcal{G}_1} \sum_{\tilde{g} \in \mathcal{G}_2(g)} \sum_{p \in \mathcal{P}} \sum_{s \in \mathcal{S}_1} FC_{g,\tilde{g},p,s}^{\text{upgrade}} \cdot y_{g,\tilde{g},p,s}^{\text{upgrade}} \quad (2)$$

The fixed operational cost for each power plant and energy storage device in the system is given by Eq. (3).

$$J_3 = \sum_{n \in \mathcal{G} \cup \mathcal{B}} \sum_{p \in \mathcal{P}} \sum_{h \in \mathcal{H}} \sum_{s \in \mathcal{S}_3} (FC_{n,p,s}^{\text{operate}} \cdot y_{n,p,h,s}^{\text{operate}} \dots FC_{n,p,s}^{\text{startup}} \cdot y_{n,p,h,s}^{\text{startup}} + FC_{n,p,s}^{\text{shutdown}} \cdot y_{n,p,h,s}^{\text{shutdown}}) \quad (3)$$

The variable operational cost for each power plant and storage device in the system is given by Eq. (4).

$$J_4 = \sum_{n \in \mathcal{G} \cup \mathcal{B}} \sum_{p \in \mathcal{P}} \sum_{h \in \mathcal{H}} \sum_{s \in \mathcal{S}_3} VC_{n,p,s}^{\text{operate}} \cdot x_{n,p,h,s}^{\text{operate}} \quad (4)$$

Equation (5) gives the cost to purchase additional power from another utility.

$$J_5 = \sum_{r \in \mathcal{R}} \sum_{p \in \mathcal{P}} \sum_{h \in \mathcal{H}} \sum_{s \in \mathcal{S}_3} FC_{r,p,h,s}^{\text{electricity}} \cdot x_{r,p,h,s}^{\text{purchase}} \quad (5)$$

The total amount of water utilized by the power generating system is given by Eq. (6)

$$J_6 = \sum_{r \in \mathcal{R}} \sum_{p \in \mathcal{P}} \sum_{h \in \mathcal{H}} \sum_{s \in \mathcal{S}_3} x_{r,p,h,s}^{\text{water}} \quad (6)$$

Planning Constraints

Equation (7) ensures that a power plant or storage unit must be built before it can become operational.

$$\sum_{\tilde{p} \in \mathcal{P}(p)} y_{n,\tilde{p},s}^{\text{build}} \geq y_{n,p,s}^{\text{on_off}} \quad \forall n \in \mathcal{G}_3 \cup \mathcal{B}, p \in \mathcal{P}, s \in \mathcal{S}_1 \quad (7)$$

Equations (8) and (9) ensure that an upgraded plant cannot operate before it has been converted.

$$\sum_{\tilde{p} \in \mathcal{P}(p,\tau)} y_{g,\tilde{g},p,s}^{\text{upgrade}} \geq y_{g,\tilde{g},p,s}^{\text{on_off}} \dots \quad (8)$$

$$\sum_{\tilde{p} \in \mathcal{P}(p,\tau)} \sum_{\tilde{g} \in \mathcal{G}_2(g)} y_{g,\tilde{g},p,s}^{\text{upgrade}} + y_{g,\tilde{g},p,s}^{\text{on_off}} \leq 1 \dots \quad (9)$$

Planning and Scheduling Constraints

Equation (10) links the capacity planning decisions to the operational scheduling decisions.

$$y_{n,p,s}^{\text{on_off}} \geq y_{n,p,h,s}^{\text{operate}} \dots \quad (10)$$

Scheduling Constraints

Equation (11) ensures each region meets its power demands for the planning and scheduling horizon.

$$\sum_{g \in \mathcal{G}(r)} x_{g,p,h,s}^{\text{operate}} + \sum_{\tilde{r} \in \mathcal{R}} (p_{\tilde{r},r}^{\text{loss}} \cdot x_{\tilde{r},r,p,h,s}^{\text{trade}} - x_{r,\tilde{r},p,h,s}^{\text{trade}}) \dots + \sum_{n \in \mathcal{B}_2(r)} p_{n,\text{or_out}}^{\text{in}} \cdot x_{n,p,h,s}^{\text{operate}} + x_{r,p,h,s}^{\text{purchase}} \dots = p_{r,p,h,s}^{\text{demand}} \quad \forall r \in \mathcal{R}, p \in \mathcal{P}, h \in \mathcal{H}, s \in \mathcal{S}_3 \quad (11)$$

Equation (12) is the energy balance for each energy storage device utilized in power generating system.

$$x_{b,p,h,s}^{\text{operate}} = x_{b,p,h-1,s}^{\text{operate}} - \sum_{n \in \mathcal{B}_2(b)} p_n^{\text{eff}} \cdot p_n^{\text{in_or_out}} \dots p_{n,p,s}^{\text{in_or_out}} \cdot x_{n,p,h,s}^{\text{operate}} \quad \forall b \in \mathcal{B}_1, p \in \mathcal{P}, h \in \mathcal{H}, s \in \mathcal{S}_3 \quad (12)$$

The standard operational limits for each of the power plants, storage units, and generators in each storage unit for the system is given by Eq. (13) through Eq. (17).

$$p_{n,p,h,s}^{\text{LB}} \cdot y_{n,p,h,s}^{\text{operate}} \leq x_{n,p,h,s}^{\text{operate}} \leq p_{n,p,h,s}^{\text{UB}} \cdot y_{n,p,h,s}^{\text{operate}} \dots \quad (13)$$

$$x_{n,p,h,s}^{\text{operate}} - x_{n,p,h+1,s}^{\text{operate}} \leq p_n^{\text{DR}} \cdot y_{n,p,h,s}^{\text{operate}} \dots \quad (14)$$

$$x_{n,p,h+1,s}^{\text{operate}} - x_{n,p,h,s}^{\text{operate}} \leq p_n^{\text{UR}} \cdot y_{n,p,h,s}^{\text{operate}} \dots \quad (15)$$

$$y_{n,p,h-1,s}^{\text{operate}} - y_{n,p,h,s}^{\text{operate}} \leq y_{n,p,h,s}^{\text{shutdown}} \dots \quad (16)$$

$$y_{n,p,h,s}^{\text{operate}} - y_{n,p,h-1,s}^{\text{operate}} \leq y_{n,p,h,s}^{\text{startup}} \dots \quad (17)$$

The limits on water availability for each region that the utility operates in is given by Eq. (18) and Eq. (19).

$$\sum_{n \in \mathcal{G}(r) \cup \mathcal{B}(r)} p_n^{\text{WU}} \cdot x_{n,p,h,s}^{\text{operate}} = x_{r,p,h,s}^{\text{water}} \dots \quad (18)$$

$$\sum_{h \in \mathcal{H}} x_{r,p,h,s}^{\text{water}} \leq p_r^{\text{WA}} \quad \forall r \in \mathcal{R}, p \in \mathcal{P}, s \in \mathcal{S}_3 \quad (19)$$

Nonanticipativity Constraints

Equation (20) and Eq. (21) enforce the nonanticipativity constraints in the planning problem.

$$y_{n,p,s}^{\text{build}} = y_{n,p,\bar{s}}^{\text{build}} \dots$$

$$\forall n \in \mathcal{G}_3 \cup \mathcal{B}, p \in \mathcal{P}, s \in \mathcal{S}_1, \bar{s} \in \mathcal{S}_1(s, p) \quad (20)$$

$$y_{g,\bar{g},p,s}^{\text{upgrade}} = y_{g,\bar{g},p,\bar{s}}^{\text{upgrade}} \dots$$

$$\forall g \in \mathcal{G}_1, \bar{g} \in \mathcal{G}_2(g), p \in \mathcal{P}, s \in \mathcal{S}_1, \bar{s} \in \mathcal{S}_1(s, p) \quad (21)$$

Optimization Problem

The multi-objective optimization problem is given the aforementioned objective functions as well as constraints and is formally defined as:

$$\begin{aligned} \min \quad & W_1 \cdot (J_1 + J_2 + J_3 + J_4 + J_5) + W_2 \cdot J_6 \\ \text{s.t.} \quad & \text{Eq. (7) - Eq. (21)} \end{aligned} \quad (22)$$

Case Study

The developed EW-N optimization framework is implemented for a power generating utility system operating in the Edwards Aquifer region of Texas. It is assumed that the utility operates in 3 separate regions within the Edwards Aquifer. Each region that the utility operates in has different energy demand, wind speed, and solar irradiance profiles. We have made considerable additions to Lara's model of the ERCOT power generating system, by allowing for uncertainties in the infrastructure planning problem, the conversion of existing power plants, the addition of energy storage devices to the system as well as exploiting the nexus connections between energy and water (Lara et al., 2018).

We utilize a set of 3 scenarios to represent the population growth and consequently growth in energy demand for each of the regions, $r \in \mathcal{R}$, that the utility operates for the 20-year planning horizon. The nominal growth scenario for each region was found by utilizing the projected population from 2020-2070 that is generated by the Texas Water Development Board (TWDB) (Texas Water Development Board, 2017). We consider an overestimate and underestimate in population growth, which is 20% above and 20% below the nominal growth as given by (TWDB). These two additional population growth scenarios each have probability of transpiring of 10%. The set of population growth scenarios for each region were mapped into a set of energy demand scenarios, $\mathcal{S}_1$.

The scheduling problem for each planning period was divided into a set of scheduling problems, $\mathcal{S}_2$, so that each planning period would have a set of representative weeks. The representative weeks are distinguished by season, Summer and Winter. These representative weeks each have solar irradiance and wind speed profiles as well as energy demand profiles based upon the planning scenario, $\mathcal{S}_1$.

The data for the nominal energy demands for the representative weeks were found by utilizing ERCOT's historical online hourly load database (Energy Reliability Council of Texas, 2018a). The nominal demands for each of the representative weeks in their respective season were found by applying k-means clustering.

The solar irradiance and wind speed profiles for each of the representative weeks and region that the utility operates in were found in a similar manner by utilizing historical data from the National Renewable Energy Laborites (NRELS) online databases (National Renewable Energy Laborites, 2018a) (National Renewable Energy Laborites, 2018b).

The capital expenditure cost, fixed operational cost and variable operational cost for the power plants were found from data in NRELS annual technology baseline report (Cole et al., 2018). The capital expenditure cost, fixed operational cost and variable operational cost for storage devices were taken from the comparison of energy storage systems by Zakeri and Syri (2015).

The interest rate utilized to bring the monetary cost to the present value was taken to be 5% per year. It is assumed that it takes one planning period for a new power plant or energy storage unit to be constructed and one planning period for the cooling technology of a storage unit to be upgraded.

The up-ramp and down-ramp limits of the NGCC and NGGT plants were taken from (Van den Bergh and Dalarue, 2015). The performance profiles for wind turbines were found via the technical data sheet for a General Electric 2.5MW-103 wind turbine (Wind Turbine Models General Electric GE 2.5 103).

Table (1) gives the set of preexisting generators as well as their corresponding cooling technology, nameplate capacity, and region.

Table 1. Preexisting Generators

Gen. Tech	Cool Tech	Capacity	Region
NGGT	NA	300 MW	2
NGCC	"once-through"	500 MW	2
NGCC	"wet-cooling"	500 MW	1
NGCC	"wet-cooling"	500 MW	3

The utility is able to purchase the following potential plants in each of the regions: NGGT with a 300 MW capacity; NGCC with a "wet-cooling" technology and a capacity of 500 MW; solar farm with a capacity of 250 MW; and wind farm with a capacity of 350 MW. The only two viable storage options in this region are batteries, with a power output of 4MW and capacity of 20MWh, and compressed air energy storage (CAES), with a power output of 300MW and capacity of 3000MWh.

Results

The algebraic model of the optimization problem was implemented using the Gurobi Python interface and consisted of 161,352 continuous variables, 193,956 binary variables, and 326,964 constraints. The program was solved on a machine with a 2.8 GHz Intel Core i7 processor and 16 GM of RAM utilizing Gurobi V8.1 (Gurobi, 2018) to an MIP optimality gap of 0.01%. For sake of example the objective function weights were both set to 0.5.

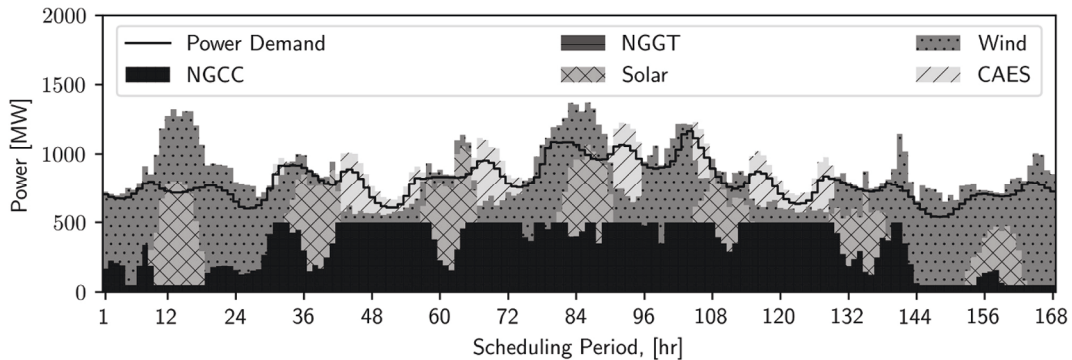


Figure 1. Power Output from the Power Plants and Energy Storage Devices for a Sample Week in the Winter

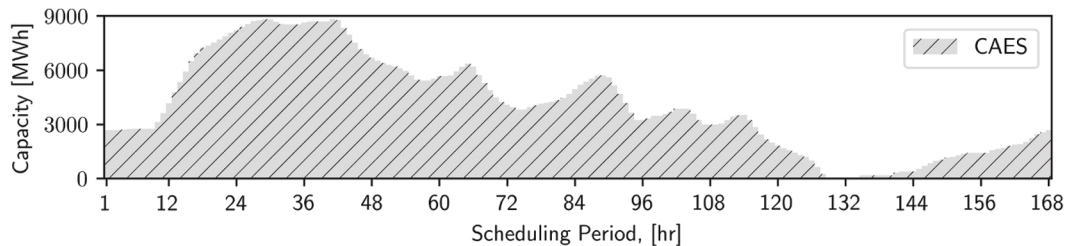


Figure 2. Capacity of the Energy Storage Devices for a Sample Week in the Winter

The results show that the power generating utility company should construct new wind farms, solar farms, and CAES devices in each of the regions it operates in during the first planning period. It was found no new nonrenewable power plants and battery storage farms should be constructed at any point in the planning horizon. It was also found the existing power plant with the “once-through” cooling technology should be shut down for all planning scenarios.

Figure (1) illustrates the power output of the different types of generators and storages devices in the fourth planning period for a representative week in winter. It should be noted in the majority of the scheduling periods the power output of generators is greater than the demand, this is due to the fact there is energy losses due to transmission when electricity is transported from one region to another. Figure (2) illustrates the capacity of all the energy storage devices in the same representative week as Fig. (1).

From inspection of Fig. (1) it clear that the utility relies heavily on renewable generators and utilizes a combination of energy storage devices and a NGCC plant to meet the demand when the generating capacity of renewable generators is insufficient to meet the energy demands. While the Fig (1) does not explicitly show it, the renewable generators are all operating at maximum capacity. This is typical for all of the representative weeks in the planning and scheduling horizons because such a decision-making strategy reduces the amount of water the power generating system utilizes.

Conclusion

In this work, we have presented an EW-N decision-making strategy for power generating utility through the use of an optimization framework. The framework allows the uncertainties in the growth of energy demands, inclusion of large-storage devices to reduce the stress brought on by intermittent renewable generators and to store excess power, the conversion of existing power plants, as well as exploits the nexus connections between energy and water. The framework was implemented for a power generating utility operating in the Edwards Aquifer and illustrates how to optimally exploit the nexus connections between energy and water.

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Table 2. Nomenclature

Name	Definition
$\mathcal{P}$	Planning horizon
$\mathcal{P}(\cdot)$	Planning period/s before a planning period
$\mathcal{P}(\cdot, \cdot)$	Planning period/s before a planning period plus additional period/s for construction
$\mathcal{H}$	Scheduling horizon
S_1	Planning scenarios
$S_1(\cdot, \cdot)$	Planning scenarios in the first time period
S_2	Scheduling scenarios
S_3	Cartesian product of S_1 and S_2
$\mathcal{R}$	Regions the utility operates in
$\mathcal{G}_1$	Existing power plants before conversion
$\mathcal{G}_2$	Existing power plants after conversion
$\mathcal{G}_2(\cdot)$	A power plant, $\bar{g} \in \mathcal{G}_2(\bar{g})$, that was previously, $g \in \mathcal{G}_1$, before it was converted
$\mathcal{G}_3$	New power plants
$\mathcal{B}_1$	New energy storage units
$\mathcal{B}_2$	Generators for the new energy storage units
$\tilde{\mathcal{B}}_2(\cdot)$	Generators for storage units in a region
$\tilde{\mathcal{B}}_2(\cdot)$	Generators for a specific storage unit
$\mathcal{B}$	Union of $\mathcal{B}_1$ and $\mathcal{B}_2$
$\tilde{\mathcal{B}}(\cdot)$	Storage generators/units in a region
FC^{build}	Fixed construction cost
$\text{FC}^{\text{upgrade}}$	Fixed cost to upgrade a power plant
$\text{FC}^{\text{operate}}$	Fixed operational cost
$\text{FC}^{\text{shutdown}}$	Fixed cost to shut down
$\text{FC}^{\text{startup}}$	Fixed cost to start up
$\text{VC}^{\text{operate}}$	Variable operational cost
FC^{elec}	Fixed cost for electricity
pdemand	Energy demand for a region
peff	Efficiency of a generator in a storage unit
pin_{out}	“1” if the generator outputs energy from or “-1” if it inputs energy into a storage unit
pLB	Lower bound on the capacity
pUB	Upper bound on the capacity– the upper bound for renewable plants is scaled based upon the hour/week
pDR	Down ramp limit on the capacity
pUR	Up ramp limit on the capacity
pWU	Amount of water utilize for the unit
pWA	Amount of water availability in a region
ploss	Transmission loss
y^{build}	Binary variable that indicates if a plant, storage generators/units is built
y^{upgrade}	Binary variable that indicates if the cooling technology of a power plant is upgraded
$y^{\text{on_off}}$	Binary variable that indicates if a plant, storage generator/unit operates in a planning period
y^{operate}	Binary variable that indicates if a plant, storage generator/unit operates in a scheduling period
y^{shutdown}	Binary variable that indicates if a plant, storage generator/unit shuts down
y^{startup}	Binary variable that indicates if a plant, storage generator/unit starts up
x^{operate}	Continuous variable (CV) that indicates the output of a plant or generator in a storage unit or the capacity of a storage unit
x^{purchase}	CV that indicates the amount of power purchased
x^{water}	CV that indicates the amount of water utilized