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Hydroelectric Power Generation and Distribution Planning Under Supply Uncertainty

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Abstract: Hydroelectric power system is a renewable energy type that generates electrical energy from water flow. An integrated hydroelectric power system may consist of water storage dams and run-of-river (ROR) hydroelectric power projects. Storage dams store water and regulate water flow so that power from the storage projects dispatch can follow a pre-planned schedule. Power supply from ROR projects is uncertain because water flow in the river, and hence power production capacity, is largely determined by uncertain whether factors. Hydroelectric generator dispatch problem has been widely studied in the literature; however, very little work is available to address the dispatch and distribution planning of an integrated ROR and storage hydroelectric projects. This combines both ROR projects and storage dam projects and formulate the problem as a stochastic program to minimize the cost of energy generation and distribution under ROR projects supply uncertainty. Input data from the Integrated Power System are used to solve the problem and run experiments. Numerical comparisons of stochastic solution (SS), expected value (EEV), and wait and see (W&S) solutions are made. These solution approaches give economic dispatch of generators and optimal distribution plan that the power system operators (PSO) can use to coordinate, control, and monitor the power generation and distribution system. The W&S solution approach provided the least cost plan. The EEV solution was worse than the SS. The PSO may invest in advanced technologies to more accurately reveal the uncertainties in the planning process, to operate at the W&S operational cost. However, the tradeoff between using the SS solution and investing in new technologies to operate at W&S solution may require rigorous feasibility study.

Keywords: stochastic solution (SS), expected value (EEV), waits and sees (W&S), power system operators (PSO), run-of-river (ROR)

Introduction

Hydroelectric power plants consist of turbine-generator sets to produce electrical energy from the potential and kinetic energy of water flow. Water is tapped from rivers and instantly supplied to turbine-generator sets, or the water is stored in a dam first and then its flow is regulated through the turbine-generator sets to generate electricity. The run-of-river (ROR) hydroelectric projects have diversion channels to tap water from rivers while storage projects use dam to store and supply water to turbines [1]. The ROR projects are cheaper to install compared to storage projects of the same capacity, which would make the per unit energy generation cost of ROR projects cheaper than the per unit generation cost of the storage projects. However, the variation of the ROR projects power output due to fluctuation in the river discharge makes the ROR projects less reliable. Furthermore, an integrated power system network is complicated. It usually consists of generation stations, transmission lines, power substations, distribution lines, and demand locations and these components are grouped as the power system components [2]. The operational characteristic of each component of the system varies based on the component capacity, location, and weather conditions among others. For example, the power loss in transmission line is a function of the conductor diameter and the length of the line. Longer transmission lines have more power loss than shorter ones and similarly a thicker power conductor has less power loss than a thinner conductor. Another important aspect of the integrated power system is the power system operator (PSO) or electricity utility. The PSO or utility coordinates, controls, and monitors the power system and it has the authority and responsibility of supplying electricity to its consumers optimally. As the number of power system components increases the PSO needs to deal with a more complex problem of optimal electrical power distribution. A comprehensive mathematical model which addresses the operational complexities of the integrated power system is necessary for economic dispatch of the hydroelectric generators and distribution planning. The purpose of this is to develop a mathematical model and propose solution approaches for an integrated hydroelectric power system that the PSO can use for optimal generation and distribution planning. Hydroelectric generators dispatch problem and electricity distribution planning problem has been widely studied in the literature that have been reviewed to work on this research. However, very little work is available to address the dispatch and distribution planning for a combined ROR and storage hydroelectric projects. Uncertainties in the generators dispatch are considered to formulate the problem as stochastic program. The distribution planning is treated as a two-stage transportation problem to minimize the cost of energy generation, transmission, and distribution under constraints such as energy demand requirement, transmission and distribution line capacity, substation capacity, and supply uncertainty from the ROR hydroelectric power plants. The problem is solved and the comparisons of stochastic solution (SS), expectation of expected value (EEV), and wait and see (W&S) solutions are made [3]. The Integrated Nepal Power System (INPS), consisting of ROR projects and storage projects, is used as a case study to run experiments. The results from these solution approaches provide an economical dispatch of the ROR and the storage projects, and optimal distribution plan to meet the energy demand [4]. Among the experimental results of the three methods, the W&S solution approach provided the least cost plan. The EEV solution was worse than the SS. The PSO may invest in advanced technology to accurately reveal the uncertainties and to operate at the W&S operational cost. However, the tradeoff between using the SS solution and investing in new technologies to operate at W&S solution may require rigorous feasibility study.

Objective of the Study

The main purpose of this research is to formulate and solve a comprehensive mathematical model that can be used to optimize hydroelectric energy generation and distribution. As described above, the hydroelectric power generation stations are far away from the consumption locations. The transmission and distribution lines and substations are required to deliver the power to the consumers located in regions far away from each other. Furthermore, the nature of demand is different from voltage level perspective; low voltage level to high voltage level (i.e. from residential consumers to industrial consumers). Due to the difference in voltage level of a transmission or distribution line the current flow through the line varies. A high voltage lines have smaller current flower than a low voltage line of same capacity. Hence, the power loss in each line and at each power system component differs from one path to another path. A generation station of having the lowest per unit cost and a transmission/distribution line of lowest power loss cost would always be the cheapest option to supply power if those components can supply all the required power. Once the capacity of a power system component is fully utilized another option needs to be explored to supply the energy demand. Hence, the goal of this research is to explore different combinations of the power system components to supply the load optimally. For example, in the following network Figure 1.1 the electrical energy demand at demand center $k = 1$ can be supplied by a various combination of generators, transmission lines, substations, and distribution lines. In an integrated power network, it is not possible to find exactly which generator is delivering its power to which of the demand; however, it is expected that by implementing the methodology presented in this thesis the power system operator can dispatch each of its generators at their optimal capacity to minimize the total energy supply cost.

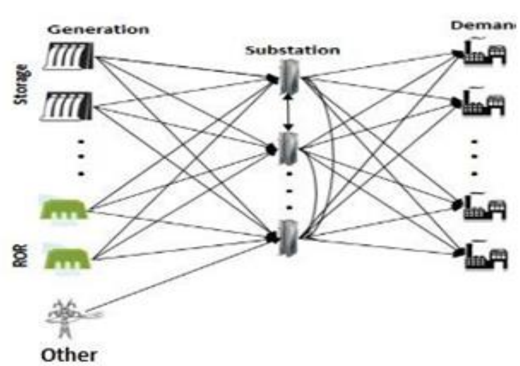

Figure 1: Power system network block diagram consisting of hydroelectric power project

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Related Work

Electrical energy is a form of energy which is produced due to the flow of electric charge particles present in the electrically conducting materials. The moving electric charge particles are called electrons and a flow of electrons is called electric current and measured in Amperes (A). The potential energy stored in charged particles is converted into kinetic energy due to the force of electric field. The capacity of an electric field to do work on an electric charge is called electric potential or voltage and measured in volts (V). An electric circuit connects an electrical energy source and an electric load. The rate at which electrical energy is transferred by an electric circuit is call electric power and it is measured in watts (W). Generally, amount of electrical energy supplied to an electric load is measured in kilowatt hour (kWh) and it is calculated by taking the time into consideration during which the electrical power was supplied [3-5]. Electric potential or voltage is induced in a closed circuit because of moving electromagnetic field. The electric potential can be fluctuating in nature (like alternating current or AC) or it can be a constant value (like direct current or DC). A battery is an example of DC voltage source. AC voltage is generated in the power plants like hydroelectric power stations. In a hydroelectric power plant, the potential energy of water stored in a water reservoir is converted into kinetic energy by the gravitational flow of water. Then the kinetic energy of water is applied to a mechanical component called turbine which runs an electromechanical generator and the electrical energy is generated by the generator. The amount of electrical power (P) in Watts produced from the water of flow rate (Q) cubic meter per second, and from head height (H) meters is given by the following equation [6]:

$$P = Q * \rho * g * H * \eta \tag{1}$$

Where, $\rho = water\ density\ in\ kg/m^3$ and

$$g = acceleration\ due\ to\ gravity\ \frac{m^2}{s}$$

$\eta = efficiency\ of\ all\ electromechanical\ components$

Several hydroelectric power plants are connected together to form an integrated power system or a grid. An integrated power system is defined as a complex network which assembles all the equipment and circuits for electrical power generating, transmitting, transforming, and distributing the electrical energy. In power systems, electrical energy is generated at the electrical power generation stations located at the different regions of the country and multiple transmission networks are used to transfer power to the demand centers scattered around the region far away from the generation stations. The integrated power system, also known as a power grid, is considered a huge source of energy (infinite bus). It is because of the fact that multiple large sized generators are connected together to supply variable energy demand in the network. The following figure shows an integrated electrical power system network.

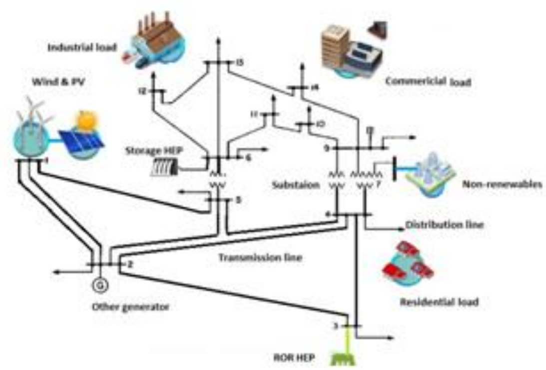

Figure 2 Integrated power systems

A brief introduction to type of hydroelectric power plant (HEP) schemes is presented as follows [9]:

Storage Projects

A storage project also called impoundment facility is typically a large hydropower system that uses a dam to store river or rain water in a reservoir. Water released from the reservoir flows through a turbine, spinning the turbine, which in turn activates a generator to produce electricity. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level. The storage projects are expensive to build because of larger dam requirement to store water and other civil structures. The dam of a storage HEP has been a huge environmental issue in recent years. It is because as the river flow is blocked by a dam, other living species in upstream as well as downstream get affected due to overflow of water or no-flow respectively. Hence, to discourage building of large water reservoirs, the governments charge some additional taxes in the investment cost of storage HEP which makes such projects more expensive [9]? Once the project is built and started generating electrical power, the operational cost is minimal as compared to similar size of other sources of energy.

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It is because the fuel required to generate electricity, which is water, is freely available.

Run-of-River Projects

Run-of-river (ROR) or diversion projects generate electricity proportional to the river's flow. A diversion channel is used to divert the river water through the turbine. Since the diversion channel does not have or lead to a water storing facility before the turbine-generator set of the ROR project, such power plant cannot regulate water flow and hence the power production is not constant. ROR projects are less reliable power plants because of variable power generation. To construct a ROR project, a natural drop in elevation is required. Utilization of natural drops in elevation make the cost of a ROR project lower than the cost of a storage project of the same capacity.

Pumped Storage

This type of hydropower works like a battery, storing the electricity generated by other power sources like solar, wind, and nuclear for later use. It stores energy by pumping water uphill to a reservoir at higher elevation from a second reservoir at a lower elevation. When the demand for electricity is low, pumped storage facility stores energy by pumping water from a lower reservoir to an upper reservoir. During periods of high electrical demand, the water is released back to the lower reservoir and turns a turbine, generating electricity.

Electricity as a Commodity

Considering the fact that there are producers, sellers, and buyers of electrical energy, electricity is a commodity that can be traded like any other products used in our daily life. Furthermore, electrical energy is an undifferentiated good that can be traded in quantity because it is easily measured. In economic terms, electricity (both power and energy) is a commodity capable of being bought, sold, and traded. Therefore, microeconomic theory suggests that consumers of electricity, like consumers of all other commodities, will increase their demand up to the point where the marginal benefit they derive from the electricity is equal to the price they have to pay. For example, a manufacturer will not produce widgets if the cost of the electrical energy required to produce these widgets makes their sale unprofitable. The owner of a fashion boutique will increase the lighting level only up to the point where the additional cost translates into additional profits by attracting more customers. Finally, at home during a cold winter evening, there comes a point where most people will put on some extra clothes rather than turning up the thermostat and face a very large electricity bill. However, due to some distinct features of electricity, it may not be totally right to compare with other commodities. These distinct features include: electricity is a real-time product, cannot be stored in bulk amount because of expensive cost and therefore must be used when it is produced; it cannot be separated from its means of transportation—transmission and distribution lines, which are owned primarily by utility companies; and it faces an inelastic consumer demand curve. This inelastic behavior of the electricity has been observed both in industrial and domestic uses. Furthermore, unlike other products, it is not possible, under normal operating conditions to have customers queue for it. The manufacturing industries that use electricity for their production process will not cut off the supply just because of a small change in electricity prices. Similarly, the residential users also will not carryout cost-benefit due to the electricity price change while turning on the lights at home or offices [10-13]. The commodities within an electricity market generally consist of two types: power and energy. Power is the metered net electrical transfer rate at any given moment and is measured in megawatts (MW). Energy is electricity that flows through a metered point for a given period and is measured in megawatt hours ($MWhr$).

METHODOLOGY

A stochastic mathematical model is developed for an integrated power system consisting of ROR and storage HEP. The mathematical model consists of two stages: first stage is to represent the storage type projects and the second stage represents the ROR projects. This model provides a solution for the amount of power generation, transmission and distribution over one-year period by the ROR and storage power plants. The study took place over a one-year period. Power generated by the storage projects is more certain than the ROR hence the probability of power generation by the storage plants during the study period is considered as 1. In contrast, in case of the ROR plants one-year period is divided into t number of seasons based on the past year's monthly power generation pattern from the ROR projects.

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Each season has a certain probability of happening over the study period. For a given season, the power plant can only generate up to a certain percentage of their installed capacity during that season. The past history data on power generation by the ROR projects during each season of a year can be used to find the probability of happening of the season and the maximum capacity of a power plant during that season. Similarly, the capacity of transmission lines, substations, and distribution lines are used to as a constraint in the model. These capacity parameters are known to the PSO or the utility at the time of detailed engineering design of the power system.

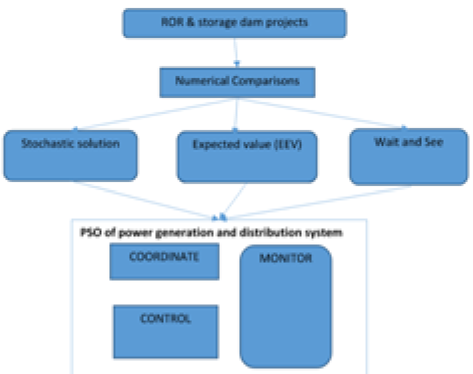

Fig 3: Data Flow Diagram

The solution approaches performed in this research are expectation of expected value solution (EEV) and stochastic solution (SS) solution. The analysis of all the three methods is presented as follows.

Expected Value Solution (EEV)

Expectation of expected value (EEV) model is constructed by replacing the expected value (EV) with its expectation. The EEV solution is performed in two stages. First, the optimization problem is solved by using the average of random scenario data (i.e. power generated by ROR projects during each season scenario) which is called the expected value (EV). This stage of solution approach provides power generated by both the ROR and storage projects. Since we use the average of the random scenarios, such an EV model is thus a Deterministic optimization problem because the uncertainty is dealt with before it is introduced to the optimization problem. Then in second stage, by fixing the values of first stage independent variables (i.e. power generated from storage projects) from the EV problem, the expectation of EV can be obtained by allowing the optimization problem to choose the values for the random variables (i.e. power generated by ROR projects). Power generated by each power plant in MW (Y-axis) during each season of a year (X- axis) is given in the following graphs:

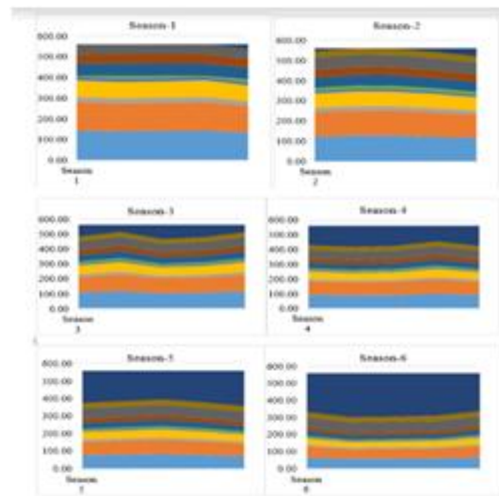

Fig 2: Decision variable values from EEV approach

As an example, in the above graph for season-1, the power generated by a storage project (let us say Kundah Pumped Storage Hydro-electric Project) is the average of 5 random values of power generation by the plant. Thus, the power output from the storage project Kundah-I is constant for all scenarios in season-1. This solution makes the first stage of EV solution. Then, the second stage solution of the EV model gives the power needs to be generated by a ROR project (let us say Kaligandaki-A) to meet the total demand. These values are different for each of the 5 scenarios in season-1. The same analysis is true for other projects as well. The graphs for season-2, 3, 4, 5, and 6 can be interpreted in the same way. As we take the average of random scenarios in EEV solution, the chances of getting inaccurate power generation is higher than using the random scenarios themselves. This is the reason why the total operational cost from EEV solution is higher than SS solution.

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Stochastic Solution (SS)

In real world problems, the decision variables (power generation, transmission and distribution here in this case) are uncertain. Their uncertainty can be modeled by a probability distribution. The solution approach of specifying the uncertainty by using the probability distributions is called stochastic solution. As the uncertainty requires approximation, the result of the stochastic solution has some inaccuracies. This research approximates the uncertainties of future weather conditions (i.e. power output from ROR plants) with a scenario-based approach. Some random scenarios are generated for each season and such scenarios determine the maximum capacity of the plant during that season. The scenario size is same as for the EV solution approach. The graph for season -1 in Figure represents the output energy generation in MW (Y-axis) during first scenario of season 1 (X-axis) and so on.

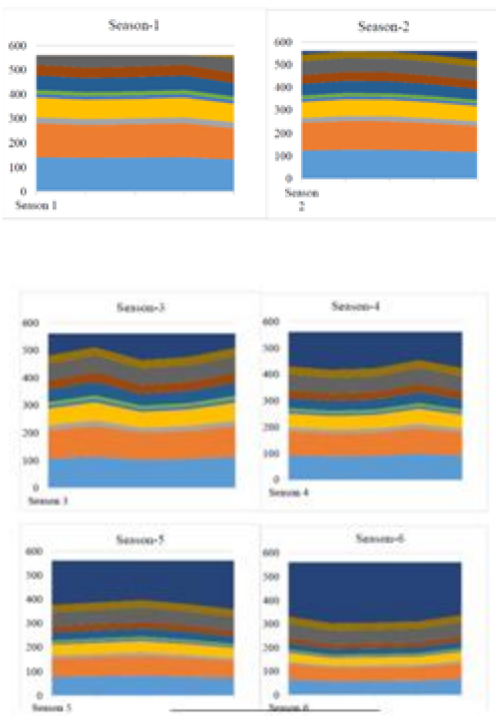

Fig 3: Decision variable values from SS approach

The approach shows the total power output from all the generators (both ROR and storage) from season-1 to season-6. Each scenario of a season is a random number with some probability of happening. This random number represents the power generated by ROR projects. When the ROR projects have lower power generation (like in season-6) due to weather change the storage projects supply the rest of the energy demand. As an example, as the water flow rate decreases from season-1 to season-6 (given in Figure) the power purchased from India, Tamilnadu of Kundah Pumped Storage Hydro-electric Project in Nilgiris District (a storage project) increases accordingly shown in Figure. Objective Function Values The objective function values from the stochastic analysis (SA) and wait & wee solution are given in following table Table 1The objective function values from SS, W&S, and EEV approach

Season	Stochastic Solution $ Per Year	Wait & See $ Per Year	EEV $ Per Year	VSS in $ Per Year	EVPI in $ Per Year
1 (0.9-1.0)	105,180,286.0	102,505,429.6	105,184,108.6	3,822.6	2,674,856.4
2(0.8-0.9)	106,382,788.9	104,025,860.2	106,382,788.9	-	2,356,928.7
3(0.7-0.8)	112,823,116.0	111,970,603.8	112,873,031.7	49,915.8	852,512.1
4(0.6-0.7)	115,744,467.2	115,337,384.1	115,764,199.6	19,732.4	407,083.1
5(0.5-0.6)	121,375,733.3	121,356,994.1	121,378,736.0	3,002.7	18,739.2
6(0.4-0.5)	121,050,682.2	120,878,194.7	121,050,682.2	-	172,487.5
Average	**113,759,512.2**	**112,679,077.7**	**113,772,257.8**	**12,745.5**	**1,080,434.5**

Total annual cost from the Table is equal to $ 256,801,050.0. This cost represents the cost of energy supply when considering the total INPS load. Here in this paper only some major portion of the total is considered which is only about 45 % of the total national peak load.

Total annual savings = $ 256,801,050.0 * 0.45 - $ 113,759,512.2 = $ 1,800,960.3

Expected Value of Perfect Information (EVPI) - is the absolute value of the difference between SS and W&S i.e.EVPI = SS-W&S = $ 1,080,434.5

Wait & See Solution (W&S)

The example output from the wait & see algorithm is plotted in the following graphs. The graph for season-1-1 in Figure represents the output energy generation in MW (Y-axis) during first scenario of season 1 (X-axis) and so on. The wait-and-see solution approach gives the value of the objective function (i.e. cost of energy supply in this research) if complete information about the decision variable was known prior to the decision is made. Thus, it can be inferred that the objective function value is obtained by running each scenario independently as if each scenario was certain and then final objective function value (cost) would be the average of all the individual costs. The cost of energy generation obtained from the W&S solution is specific to each scenario, which is always less than the cost obtained if the random scenarios are used like in SS approach.

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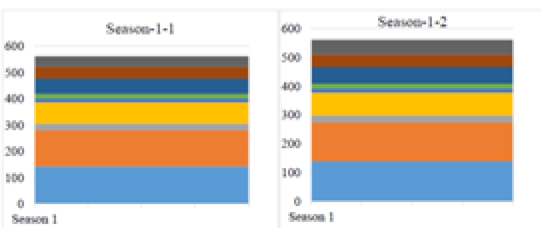
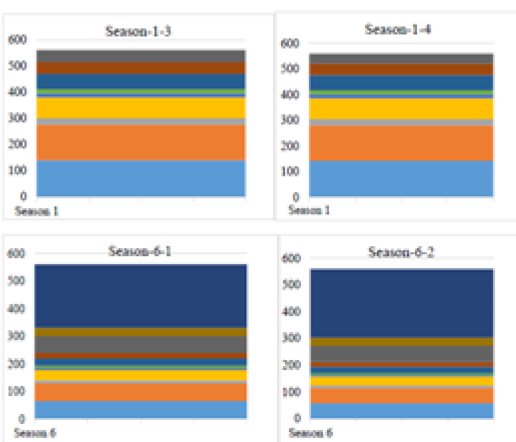
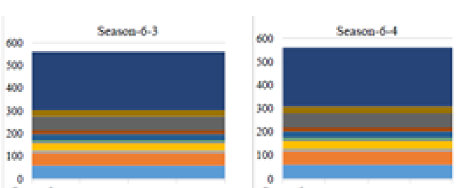
Let us take an example of the graph for season-6-5 in Figure 4.6 to explain the results of the W&S approach. Scenario 5 of the season 6 is a random number, which represents the power generated by the ROR projects. For a moment, the power generated by the ROR project during season-6 is certain, which equals to the random scenario-5 of season-6. The PSO now have perfect information about how much power generation will be obtained from ROR projects in the future. Then, the storage projects are dispatched accordingly to meet the total demand. Similar dispatch strategy can be applied for other scenarios of the season-6. Finally, the average of the 5 solutions (objective function from 5 scenarios) is computed to get the cost of energy supply during season- 6 from W&S algorithm. Same analysis is true for season-1, 2, 3, 4, and 5 as well.







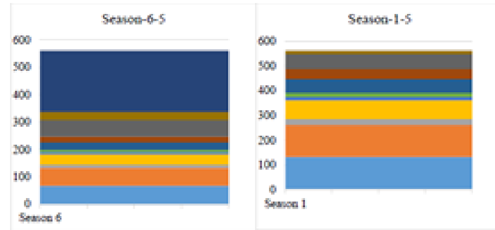


Fig 6: Decision variable values from W&S approach

Total cost per year obtained from the mathematical model using W&S approach = $ 112,679,077.76 which cheapest among all three solutions explained above

Conclusions

In this paper, a stochastic mathematical model was developed for an integrated power system that consists of both the run-of-river and storage projects. The ROR projects are cheaper to install and operate than the storage hydroelectric project of the same capacity. In addition, the ROR projects are environmentally friendly compared to the storage projects, because ROR projects have simple water diversion channel. However, due to the fluctuating energy output from the ROR power plants they pose a reliability threat to the integrated power system. A mathematical model that could predict the energy output from the ROR by using the probability of future weather conditions would help the power system operator to schedule all power plants in an optimal way. The optimal solution would ensure load and generation balance at all times and also the total cost of energy supply would be minimum. Kundah pumped storage Hydro-Electric Project is planned in Nilgiri District of Tamil Nadu was taken as a case study power system in this research. Power produced from the ROR depends on the available water discharge in the river which varies continuously with weather conditions. On the other hand, the storage projects are designed to produce power at their installed capacity independent of the temporary weather change. The operational cost of a power plant is different from another power plant because of the power plant's location, its size, and maintenance cost. As an example, a power plant located in the remote area of a country would require larger investment due to required civil structures like access roads. This investment cost affects the per unit energy cost of the power plant during its operation. The generated power from the generators is supplied to demand centers at distant location via power transmission and distribution lines and substations. The

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power loss cost in the lines and substations and their operational and maintenance cost is not the same for all the components. Power loss in the transmission and distribution lines depends on the length of the line and diameter of the power-carrying conductor. A combination of a generator, a transmission and distribution line, and a substation to supply a demand could be cheaper than another combination of the different generators, transmission and distribution lines, and substations due to the cost difference. In addition to the cost parameters, the power system components have some constraints like maximum capacity of the component, which restricts the further operation of that component even though it would be cheaper to meet the energy demand. As the number of these power system components increases the possible combination also increases, which makes the problem of optimal energy supply more complex. The mathematical model presented in research considered all the possible combinations and solves the model to give a most economical way of supplying the load by taking into account the system constraints.

Benefits for the energy users

The mathematical model developed is called a two-stage stochastic model which consists of two stages: first stage is to represent the storage type projects and the second stage represents the ROR projects. This model provided a solution for the amount of power generation, transmission and distribution over one-year period by the ROR and storage power plants. Power generated by the storage projects is more certain than the ROR, hence, the probability of power generation by the storage plants during the study period was considered as unity. In contrast, in the case of ROR plants one-year period was divided into six seasons based on the past year's power generation pattern from the ROR projects. Each season had a certain probability of happening over the study period and the power plant could only generate up to a certain percentage of their installed capacity during that season. The historic data on power generation by the ROR projects was used to find the probability of occurrence of the season and the maximum capacity of a power plant during that season. The problem was solved and comparisons of the stochastic solution (SS), expected value (EEV), and wait and see (W&S) was made. The results from these solution approaches provided an economical dispatch of the ROR and storage projects and optimal distribution plan to meet the energy demand. The PSO should interpret the results from these solution techniques as follows: The months in a year when the power plants can generate power from 90% to 100% of their installed capacity were grouped into the season-1. Similarly, the months in a year when the power plants can generate power from 80% to 90% of their installed capacity were grouped into the season-2 and so on. The results of the decision variables showed that the power generated by a ROR plant during season-1 was more than the power generated by the same ROR plant in other seasons. This means the storage power plants should be operating at minimum capacity and store some water during season-1 so that the stored water could be used to run the plants at increased capacity during other seasons. If the domestic generation was not sufficient to meet the energy demand, then power should be purchased from out of state (like from India in case of INPS). For all the experimental runs, the W&S solution approach provided the least cost plan. The EEV solution was worse than the SS. The PSO may invest in advanced technology to more accurately reveal the uncertainties to operate at the W&S operational cost. However, the tradeoff between using the SS solution and investing in new technologies to operate at W&S solution may require rigorous feasibility study. Some of the benefits for the energy users, power producers, and the government from the proposed methodology are: Reliable power supply for the customers. Optimal use of ROR projects which would reduce the cost and also reduce the environmental effects caused by storage power plants. This would benefit the power producers and the government. Optimal use of available domestic power plants. In addition to the optimal energy generation and distribution planning for an existing system, the government can use the given mathematical model in energy planning. This can be achieved by using a forecasted energy demand (in place of current demand) for a certain planning horizon, the solution of the proposed mathematical model would give an idea of what should be the strategy of energy generation and distribution in coming future. If the solution produces an infeasible solution due to greater forecasted demand than total available generation then the decision maker can virtually place a new power plant with some estimated operational cost to see what

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would be the best way to supply the future need of energy. In addition to the above benefits, this research adds a contribution to the state-of-art by presenting the integrated power system network as a two-stage transportation problem and minimizing the total cost of energy supply to the customers. As given in the literature review section, various research articles can be found in the field of deterministic, stochastic as well as large scale optimization that present different objective functions and methodologies of solving problems. Some major objective functions include the optimal scheduling hydro-thermal unit, optimization of water content in the reservoir for a storage hydroelectric project, minimization of carbon emission from power plants, scheduling of electrical loads like electric vehicles and thermostatically controlled loads, and optimal sizing and sitting of DGs. These articles present methodologies for optimization only in the generator side or in demand side. However, this thesis presents a stochastic optimization methodology that considers all the components of the integrated power system (i.e. generators, transmission and distribution lines, and substations). Power produced by the generators and transmitted to the distribution substation makes the first stage of the problem while the power distributed from the substations to the demand centers makes the second stage of the two-stage transportation problem.

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