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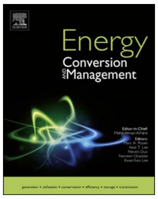

Substitution of coal power plants with renewable energy sources – Shift of the power demand and energy storage

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ABSTRACT

Because of their Global Climate Change contributions, it is desirable to reduce the amount of the global CO_2 emissions. One of the ways to accomplish this is the substitution of coal with renewable energy sources, most notably wind and solar. However, the availability of wind energy and of insolation does not follow the diurnal and annual demand patterns of electric power. The large-scale substitution of coal with wind and solar significantly shifts the demand for the rest of the power producing units. When the contribution of wind and solar exceeds approximately 25% of the total annual energy produced, there are time periods within a year when excess electricity is produced that must be wasted/dissipated. This presents a severe constraint for the substitution of coal-generated electricity with renewables. At such production levels diurnal or seasonal storage of energy becomes necessary and hydrogen storage offers the best alternative. Based on the hourly, electricity demand of a region in North Texas, which has very high availability of wind and solar energy and is considered prime region for renewables, extensive calculations are made for: (a) the solar and wind rated power that are necessary for the substitution of part or all the power currently supplied by a coal-fired power plant; and (b) the storage requirements for this substitution. Significant seasonal and diurnal energy storage, on the order of 250,000 m^3, is required for the total substitution of coal in the region. The calculations also reveal that the substitution of coal with the renewable energy sources may be optimized for minimum energy storage capacity.

1. Introduction

The global production of electricity has been continuously increasing in the last 120 years. Since 1980 the average annual rate of global electric energy growth is 4.93% and this implies that the electricity demand doubles every 14.5 years [1–3]. Coal is still the major primary energy source for the production of electric energy with coal power plants producing globally more than 39% of the total electricity [1]. Because the combustion of coal in power plants produces CO_2, the Greenhouse Gas with the highest environmental impact, and contributes significantly to the observed Global Climate Change (GCC) in the last thirty years there have been several regional and international efforts to decrease the use of coal for the production of electricity and curb the production of CO_2 emissions. Despite these international efforts, the relative fraction of coal for the production of electric energy has been slowly increasing, from 37% in 1980 to 39% in 2014. In the same period, the contribution of renewables other than hydroelectric increased from 0.7% in 1980 to 6.8% in 2015 [2]. If the global CO_2 emissions are to be reduced, the substitution of coal power plants with renewable energy sources – primarily wind and solar that are widely available – becomes an important task in regional and national energy planning and management.

The production of electric power in all the electricity grid systems is dictated by the instantaneous demand for power. Base-load, intermediate-load, and peak-load units balance the power demand and supply in all the regions of the globe. Wind and solar energy are clean renewable sources, but they are not available at all hours of the year. Even when they are available, they may not have the intensity to supply the entire demand for power. For example, during the evening of July 17, when a great deal of electric power is demanded by the air-conditioning systems in Texas (and all hot regions on earth), there is zero insolation and the weak breezes are insufficient to satisfy the high power demand. The substitution of a high fraction of the produced electricity from coal with renewable sources has a second consequence. Coal power plants are base-load plants; they operate with Rankine steam cycles; and cannot be switched on and off frequently. Their production capacity may be reduced to 80% of their rated capacity, but the plants must be continuously in operation, day and night. Frequent

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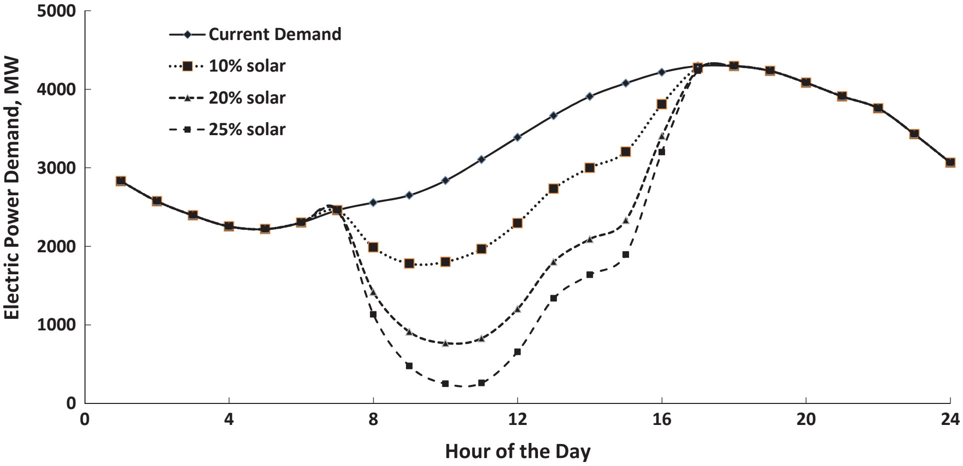

Fig. 1. Shift of the power demand for the non-solar power plants in the San Antonio, Texas, region when 10, 20, and 25% of the electric energy is produced by solar units.

generation stoppages and significant power reduction would damage the machinery of the steam units.

If a region decided to "become green," and produce a high fraction of the electric energy by solar installations, which only produce at daylight hours, there will be a significant reduction of the electric energy demand from the non-solar units during the daylight hours, when all the solar energy is produced. This negatively affects the operation of the base-load units for the parts of the day, when the insolation is high, but the power demand is not. Fig. 1 depicts the expected modification of the summertime weekday power demand in San Antonio, Texas, when 10, 20 and 25% of the buildings in the City become Zero-Energy Buildings (ZEBs) and produce by insolation as much energy during an entire year as they consume, while still connected to the electricity grid [2]. It is observed in the figure that the power demand from the non-solar power units shifts from the solid line (which represents the current demand) to the broken lines that are labeled by the fraction of the total energy generated by solar units during the 24 h. The area enclosed by the broken lines and the solid line represents the fraction of electricity generated by insolation during the day. The demand curves for the non-solar units exhibit a large dip during the early daylight hours and have been called *U-shaped demand* curves or *duck curves* [4,5]. The sharp dip of the curves during the early morning hours implies that the power production from non-solar units in the region must be reduced accordingly in order to accommodate the energy production of the solar units. In the case of San Antonio, if 28% of the daily energy is supplied by photovoltaic (PV) units, all the other power plants in that region would have to shut down between 9:00 and 11:00 am. This represents a severe limitation on the production of solar-generated electricity for the region. This is not a regional problem that applies to San Antonio alone. The same limitations would apply to all the other regions where substitution of fossil fuel-generated energy with solar energy is desirable.

Similar trends for the power demand of the non-renewable units would occur if a fraction of electricity higher than 25% were produced by wind power. During the hours of high wind velocity the power demand for the non-wind units becomes zero or negative, which implies that some of the produced power must be dissipated and wasted.

Because large, base-load steam units – primarily coal and nuclear – cannot adjust their power production as frequently as the production by the renewable energy units fluctuates, the regions are served by electricity grids will have to pursue a combination of the following [2,4]:

(a) Reduce the number or completely eliminate the current base-load power plants, both coal and nuclear, and substitute them with other units, e.g. gas turbines, that may start and stop at will following the regional power demand. The substitution requires substantial investment that will make electricity significantly more expensive. Also the CO_2 emissions are reduced but not eliminated with this option.
(b) Offer incentives (e.g. power pricing) to partly control and adjust the electricity demand of the consumers in the region in a way that increases the electric power demand during the hours of high production from renewables. This may be easier accomplished for solar energy, which is periodically variable, and becomes very difficult for wind energy. This solution is only partly effective because full control of the electric power demand is impossible to achieve.
(c) Invest in utility-level storage capacity that would store the excess power produced during the high production hours and seasons. This will enable many of the base-load plants – most notably the nuclear power plants that produce cheap electricity and do not emit CO_2 – to operate in conjunction with the renewable units.

The control/adjustment of the power demand has been the subject of several recent studies. A study for the island Oahu (state of Hawaii) revealed that the substitution of 40% of the total electric energy from wind and solar entails "significant operational challenges," especially during periods when the electricity generation from renewables diverts from the forecasts. The study concluded that demand control through electricity pricing has the potential to smoothen the power system operation and partly balance demand and supply [6]. Power demand adjustment in combination with chilled water storage for air-conditioning, has been suggested as the solution to using a high fraction of electricity from renewables and maintain grid stability and reliability in a micro-grid system [7]. The chilled water solution has been adopted successfully in the five terminals of the DFW airport, but it only shifts the power demand to the night hours and does not necessarily increase the use of renewables [2]. A more recent study has highlighted the importance of energy storage when an increasing fraction of electric energy is derived from renewables and explained the link between the shape of the electric power demand curve and the amount of the storage system capacity [8]. The study correctly emphasized the distinction between the energy produced and the instantaneous power needed by the consumers. Another recent study examines the data for the residential demand for power, highlights the necessity for energy storage and offers alternatives that would make buildings and clusters of buildings grid-independent and reliant on renewable energy only [9]. The currently available energy storage methods, their capabilities and their estimated costs have been the subjects of two recent studies [10,11].

This paper examines the effect of the partial or total substitution of coal-derived electric power by a combination of wind and solar units in the North Texas region and highlights some the limitations that would accompany this substitution. The region is typical of the Southwest part