Research Article
Reduction in Pollutants Emission by Increase in Renewable Penetration: A Case Study

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Abstract: For environmental friendly electricity supply system, the global utilization of Renewable Energy Resources (RES) and Distributed Energy Storage (DES) facilities is increasing rapidly. The environmental benefits possible when utilizing renewable power generation along with the conventional power production are analyzed here. Considerable amounts of pollutants emission from power generation based on fossil fuels can be reduced with high penetration of RES. The aim of this study is to increase the awareness on the benefits achieved by the utilization of renewable power. A generalized model for analyzing the impacts of renewable penetration on the amount of pollutants emission from hybrid plants is proposed here with a case study. It is concluded that the RES based power generation can play a vital role for green and clean energy production.

Keywords: Energy storage, environment, pollutants emission, renewable energy, renewable penetration

INTRODUCTION

The earth's atmosphere is being overloaded with Greenhouse Gases (GHG), which may create large-scale disorders in climate with severe consequences. Burning of fossil fuels accounts for major part of the GHG emissions. At present fossil fuels like coal, oil and natural gas supply approximately 86% of global primary energy needs and major share of world electricity production is this fuel based thermal plants (Akorde et al., 2010). The emissions from such plants cause global warming, acid rain, urban smog and hence are resulting in severe damage to the environment. It is anticipated that the failure to reduce pollutants emission from burning fossil fuels will result in an increase in the average global temperature in the range of 1.4 to 5.8°C during 1990 to 2100 period (Saidur et al., 2011).

Fossil fuel based power plants account for more than 66% of global electricity production and about 40% of this production is contributed by the coal fired thermal power plants alone (Jamel et al., 2013; Pazheri et al., 2012). The main pollutants from fossil fuel based plants are CO₂, SO₂, NOₓ and particulate matter (PH₁₀), etc. The air pollution particles with size between 2.5 to 10 µm are called PH₁₀ and include smoke, dirt, dust, mold and pollen, etc. Due to the effect of pollutants from the fossil fuel based plants, about 0.3 million people die annually worldwide and pollutants from coal fired plants alone kill about 170000 people every year (Polya, 2008). A research by Fraunhofer institute states that about 117 $/MWh is being currently paid by European citizens for health and environmental damages caused by the generation of electricity using the conventional thermal power plants (Nathan, 2012). It is projected that power stations will contribute the major share of GHG emissions for the next 100 years (Akorde et al., 2010) as shown in Fig. 1. Thus, awareness on climate changes is forcing the policy of
accelerated utilization of renewable energy sources for electricity production. Electricity production using renewable energy resources reduces environmental impacts of GHG and produces least amount of secondary wastes. Natural resources like solar energy, wind power, hydropower, biomass energy and geothermal energy are the major RES for clean and green energy production. According to Green Budget Germany (GBG) research, the power generation from conventional plants is more expensive than the generation from the RES based plants if the cost paid for health and environmental damages is also considered (Nathan, 2012). RES supplied approximately 16.6% of total world energy consumption in 2010. This energy consumption increased by 22% between 2000 and 2010. Furthermore, it is estimated to increase by more than 42% during the 2010-2020 periods (Jamel et al., 2013; Panwar et al., 2011). Thus more use of RES based energy is expected to continue, which should be good news for environment.

In order to ensure high penetration of RES to grids, it is required to use energy storage facilities. Energy storage facilities can ensure clean, secure and continues supply of energy from more distributed and intermittent renewable resources. The current global storage capacities have exceeded 127.9 GW. Pumped Hydro Storage (PHS) is the fundamental storage method which alone accounts for 95% of these storage capacities (IRENA, 2012; SETIS, 2011). Deep cycle batteries with capacity ranging from 17-40 MWh and efficiency of 70-80% are commonly used in power system applications. Golden Valley Electrical Association (GVEA) in Alaska installed a battery energy supply system with nickel cadmium batteries that supplies more than 40 MW for 15 min (DeVries et al., 2004; Divya and Østergaard, 2009). Super capacitors represent another high power density electrochemical energy storage system while Super conducting Magnetic Energy Storage (SMES) enables energy storage in magnetic field at very low temperatures. SMES devices with capacity of 1-10 MW and efficiency of 98% are commercially available (Hall and Bain, 2008; Ibrahim et al., 2008). Energy is also stored in Compressed Air Energy Storage (CAES) systems by high pressure compressed air storage. The batteries of electric drive vehicles have also been recognized as means for renewable energy storage. Other types of energy storage systems including flywheel storage, thermal storage and natural gas storage, etc., are also widely used in power system applications.

Production and storage of renewable energy at times when there would be a surplus of its availability or at off-peak load hours and the reuse of such stored energy during its unavailable periods helps to increase the effective renewable energy penetration level to the grid. High potential renewable area could utilize storage facilities to harvest and utilize maximum green energy. In 2007, 20% of total electricity demand of Denmark was met by wind power alone and was targeted to increase the penetration level to 50% by 2025 by installing more efficient energy storage facilities (Divya and Østergaard, 2009). Due to the rapid growth of the renewable energy and energy storage technologies, the utilization of RES based electricity generation is increasing in all parts of the world.

The main objectives of this study are to analyze various pollutants emissions due to the generation of electricity from fossil fuels and to calculate the reduction of these pollutants due to the presence of renewable power. The amount of reduction of these pollutants with the utilization of RES and their environmental benefits are discussed here. The analysis is carried out using MATLAB simulations.

**METHODS OF ANALYSIS**

If $W_f$ is the weight of fuel fired per hour in tonnes (ton) and $C_{vf}$ is the calorific value of fuel. Then the boiler input power in MW due to the burning of fossil fuel is expressed as:

$$P_{IB} = \frac{W_f \cdot C_{vf}}{3600}$$

(1)

The calorific value of fuel is expressed in kJ/kg and given as follows (Mesroghli et al., 2009):

$$C_{vf} = 327.8C_f + 1419H_f - 137.9O_f + 92.6S_f + 637$$

(2)

Here, $C_f$, $H_f$, $O_f$ and $S_f$ represent the percentage weight of the carbon, hydrogen, oxygen and sulphur in the fuel and can be calculated by the ultimate analysis of fuel used (Stull, 2003).

The power output of the generator $P_G$ in MW is expressed as:

$$P_G = \eta_p P_{IB}$$

(3)

where, $\eta_p$ is the overall efficiency of power plant which includes the efficiency of the boiler, the turbine as well as the generator, etc.

The power generated by the renewable energy resources $P_R$ is generally variable. Hence it is considered as a variable negative load. Therefore $P_R$ is deduced from the power demand $P_D$. In a system, $P_D$ is generally varying with time and depends on the weather and many other factors. To ensure power balance, the total power generation $P_G$ must equal the total demand plus the transmission line loss $P_L$. Hence:

$$P_G = P_D + P_L - P_R$$

(4)

$$P_R = xP_D$$

(5)
The amounts of pollutants produced by the burning of fossil fuel at power plants depend upon the weight of fuel used, emission factor and boiler efficiency, etc. A generalized expression for the amount of pollutant ‘i’ emitted in ton/h is written as follow (ISCC, 2011; NPI, 1999):

\[
P_L = B_1 P_G^2 + B_2 P_G + B_0 \quad (6)
\]

\[
E_{fi} = W_{ref} (1 - \eta_{cl}/100) \quad (7)
\]

where, \( x \) is the renewable energy penetration level (the ratio of renewable energy extracted to the total load demand):

\[
P_L = B_1 P_G^2 + B_2 P_G + B_0
\]

\[
E_{fi} = \sum_{i=c,s,n,p} (\alpha_i P_G^3 + \beta_i P_G^2 + \gamma_i P_G + \delta_i)
\]

\[
E_I = \sum_{i=c,s,n,p} (\alpha_i P_G^3 + \beta_i P_G^2 + \gamma_i P_G + \delta_i)
\]

\[
S_O_2 = 3.11 \times 10^{-6} X^{1.905}
\]

\[
N_O_2 = 3.13 \times 10^{-7} X^{2.4287}
\]

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\[
N_O_2 = 3.13 \times 10^{-7} X^{2.4287}
\]
Table 4: Pollutants emissions (ton/h) in case B

<table>
<thead>
<tr>
<th>PD (MW)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>X = 0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>55.8510</td>
<td>99.3220</td>
<td>141.0600</td>
<td>181.1800</td>
<td>219.8300</td>
<td>257.1500</td>
<td>293.2600</td>
<td>328.3100</td>
<td>362.4300</td>
<td>395.7500</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.3661</td>
<td>0.6844</td>
<td>0.9896</td>
<td>1.2825</td>
<td>1.5643</td>
<td>1.8359</td>
<td>2.0983</td>
<td>2.3526</td>
<td>2.5996</td>
<td>2.8406</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.1968</td>
<td>0.3815</td>
<td>0.5667</td>
<td>0.7530</td>
<td>0.9410</td>
<td>1.1312</td>
<td>1.3242</td>
<td>1.5207</td>
<td>1.7211</td>
<td>1.9261</td>
</tr>
<tr>
<td>PH₁₀</td>
<td>0.0159</td>
<td>0.0300</td>
<td>0.0435</td>
<td>0.0565</td>
<td>0.0689</td>
<td>0.0807</td>
<td>0.0919</td>
<td>0.1025</td>
<td>0.1125</td>
<td>0.1219</td>
</tr>
<tr>
<td>X = 10%</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>51.4080</td>
<td>90.7920</td>
<td>128.7600</td>
<td>165.4000</td>
<td>200.8000</td>
<td>235.0800</td>
<td>268.3200</td>
<td>300.6300</td>
<td>332.1100</td>
<td>362.8500</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.3336</td>
<td>0.6220</td>
<td>0.8997</td>
<td>1.1673</td>
<td>1.4256</td>
<td>1.6753</td>
<td>1.9172</td>
<td>2.1519</td>
<td>2.3801</td>
<td>2.6027</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.1783</td>
<td>0.3446</td>
<td>0.5113</td>
<td>0.6787</td>
<td>0.8474</td>
<td>1.0176</td>
<td>1.1900</td>
<td>1.3648</td>
<td>1.5425</td>
<td>1.7236</td>
</tr>
<tr>
<td>PH₁₀</td>
<td>0.0144</td>
<td>0.0272</td>
<td>0.0396</td>
<td>0.0514</td>
<td>0.0628</td>
<td>0.0737</td>
<td>0.0842</td>
<td>0.0941</td>
<td>0.1036</td>
<td>0.1126</td>
</tr>
<tr>
<td>X = 30%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>42.4640</td>
<td>73.5130</td>
<td>103.7000</td>
<td>133.0600</td>
<td>161.6500</td>
<td>189.5000</td>
<td>216.6600</td>
<td>243.1700</td>
<td>269.0900</td>
<td>294.4600</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.1414</td>
<td>0.2709</td>
<td>0.4005</td>
<td>0.5306</td>
<td>0.6613</td>
<td>0.7927</td>
<td>0.9252</td>
<td>1.0589</td>
<td>1.1940</td>
<td>1.3308</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.0115</td>
<td>0.0216</td>
<td>0.0314</td>
<td>0.0409</td>
<td>0.0502</td>
<td>0.0592</td>
<td>0.0679</td>
<td>0.0763</td>
<td>0.0844</td>
<td>0.0923</td>
</tr>
</tbody>
</table>

Fig. 2: Plot of pollutants emissions as a 3rd order polynomial against demand

Let $E_{kx}^{tx}$ and $E_{k}^{t}$ be the amounts of total emissions with renewable power at penetration level $x$ and without renewable power, respectively. Similarly, $E_{ki}^{tx}$ and $E_{ki}^{t}$ be the amounts of pollutant $i$ with and without the renewable power, respectively. Here $k$ is equal to a or b for Case A or Case B, respectively.

The amounts of various pollutants emitted with the generation of required power demand for Case A and Case B are given in Table 3 and 4, respectively. The results show that the amount of each pollutant emitted at a specified power demand is higher in Case A than the corresponding value for Case B. Compared to the other pollutant, the emission of CO₂ pollutant is significantly higher while PH₁₀ pollutants is almost negligible. The amount of CO₂ emission accounts for almost 99% of the total pollutant emitted at a specific demand. At a demand of 300 MW and with 30% renewable penetration level, the emissions of CO₂ and PH₁₀ pollutants in Case A are almost 238 and 0.063 ton/h, respectively, while the corresponding amounts in Case B are almost 190 and 0.059 ton/h, respectively.

The variation of the amount of overall pollutants with power demand for Case A is shown in Fig. 3 and that for Case B is shown in Fig. 4. A significant reduction in the total amounts of pollutants emission in both cases is achieved by utilizing renewable power along with conventional power. While generating a power of 200 MW by coal fired power plant, the amounts of total pollutants emitted are more than 127 and 100 ton/h for Case A and Case B, respectively. However, if 30% of this demand is met by RES based plants, then these amounts are decreased to almost 95 and 74 ton/h, respectively.

The variation of total pollutants emission with daily load demand variation is given in Table 5. The supply of peak demand of 247 MW in the presence of 20% of emission control and renewable power with 30% penetration level emits only 162 tonnes pollutants.
per hour and this amount is less than the amount of pollutants emitted while generating a demand of 150 MW in the absence of emission control devices and renewable power usage. A hybrid power plant which produces power by utilizing conventional and renewable energy can reduce the amount of pollutants emission in a significant manner. The presence of emission control devices and energy storage devices increases the potential of clean power production in such plants. More than 25% pollutants can be reduced if renewable power at 10% penetration is used with controlling emission by 20% as shown in Fig. 5. Moreover, it is clear from Fig. 5 that this percentage reduction in pollutants emission increases by more than 40% upon increasing the renewable penetration level to 30%. In general, as expected, the amount of pollutants emission will increase with increase in power demand and will decrease with increase in the renewable power penetration level as shown by these results. The share of renewable power impacts a considerable reduction in the pollutants emissions from power plants and therefore decreases the undesirable environmental effects and damages. Thus, a significant amount of cost paid by the citizens for the health related issues can be decreased by using renewable energy resources.

Table 5: Overall pollutants emission with daily load demand

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>PD (MW)</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E_t</td>
<td>E_{10}</td>
<td>E_{20}</td>
</tr>
<tr>
<td></td>
<td>E_t</td>
<td>E_{10}</td>
<td>E_{20}</td>
</tr>
<tr>
<td>0</td>
<td>57</td>
<td>80.91</td>
<td>74.60</td>
</tr>
<tr>
<td>2</td>
<td>76</td>
<td>101.76</td>
<td>93.47</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
<td>122.29</td>
<td>112.09</td>
</tr>
<tr>
<td>6</td>
<td>152</td>
<td>182.05</td>
<td>166.43</td>
</tr>
<tr>
<td>8</td>
<td>152</td>
<td>182.05</td>
<td>166.43</td>
</tr>
<tr>
<td>10</td>
<td>190</td>
<td>220.45</td>
<td>201.48</td>
</tr>
<tr>
<td>12</td>
<td>171</td>
<td>201.39</td>
<td>184.07</td>
</tr>
<tr>
<td>14</td>
<td>133</td>
<td>162.43</td>
<td>148.56</td>
</tr>
<tr>
<td>16</td>
<td>209</td>
<td>239.25</td>
<td>218.66</td>
</tr>
<tr>
<td>18</td>
<td>247</td>
<td>276.08</td>
<td>252.40</td>
</tr>
<tr>
<td>20</td>
<td>171</td>
<td>201.39</td>
<td>184.07</td>
</tr>
<tr>
<td>22</td>
<td>95</td>
<td>122.29</td>
<td>112.09</td>
</tr>
<tr>
<td>24</td>
<td>57</td>
<td>80.91</td>
<td>74.60</td>
</tr>
</tbody>
</table>
CONCLUSION

A case study of environmental benefits achieved by using an increased renewable penetration level is carried out using MATLAB simulations. A generalized model to calculate pollutants emission in the presence of renewable power is discussed in this study. The reductions in the amount of various pollutants emitted from the power plants at different levels of renewable power penetration levels are presented and discussed. The decrease in the amount of pollutants reduces the environmental damages and health concerns caused by the environmental pollution. The cost paid for health care and the environmental damages are also decreased with high renewable penetration is also decreased. Thus although, on the surface RES power may appear costly, its overall costs are less than the corresponding costs associated with the conventional power plants.

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REFERENCES


