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A Genetic Algorithm Based Economic Dispatch (GAED) with Environmental Constraint Optimisation

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Abstract- **The role of renewable energy in power systems is becoming more significant due to the increasing cost of fossil fuels and climate change concerns. However, the inclusion of Renewable Energy Generators (REG), such as wind power, has created additional problems for power system operators due to the variability and lower predictability of output of most REGs, with the Economic Dispatch (ED) problem being particularly difficult to resolve. In previous papers we had reported on the inclusion of wind power in the ED calculations. The simulation had been performed using a system model with wind power as an intermittent source, and the results of the simulation have been compared to that of the Direct Search Method (DSM) for similar cases. In this paper we report on our continuing investigations into using Genetic Algorithms (GA) for ED for an independent power system with a significant amount of wind energy in its generator portfolio. The results demonstrate, in line with previous reports in the literature, the effectiveness of GA when measured against a benchmark technique such as DSM.**

Index Terms-- **Genetic Algorithms, Economic Dispatch, Renewable Energy Generators, Environmental Constraints**

I. INTRODUCTION

The role of renewable energy in power systems is becoming more significant due to the increasing cost of fossil fuels and climate change concerns. However, the inclusion of Renewable Energy Generators (REG), such as wind power, has created additional problems for power system operators due to the variability and lower predictability of output of most REGs, with the Economic Dispatch (ED) problem being particularly difficult to resolve.

The renewable energy sources available in general can be classified into 2 groups: geophysical and bio-energy. Geophysical energy includes hydro, wind, geothermal, solar, tidal, and wave energy, whereas bio-energy includes energy derived from waste and living creatures. Both types of energy have different properties. Much of geophysical energy output is intermittent, less predictable and not easy to store, while bio-energy is much more predictable and can be easily stored.

Wind energy, produced by wind turbines, is one of the fastest growing energy sources due to its large potential availability and its mature technology [1]. Therefore, in our initial investigations wind turbines were chosen to represent intermittent renewable energy in the simulations. In addition to wind turbines, the use of bio diesel as back up power was also considered as it has a fast ramp rate and is easily stored; therefore it is able to compensate for the intermittent nature of wind energy with its variability and lower predictability of its output [2]. These additional complexities also introduce several implications such as the need to understand wind power characteristics, and the consideration of additional constraints such as reserve requirement and ramp rate capability [3-8]. Traditionally ED calculations principally seek for the most economical operation of the generation mix for satisfying load demand and other technical generator constraints. However, due to increasing concerns regarding environmental issues, such as reducing carbon emissions and other gas pollutants, for tackling climate change and achieving sustainable energy generation, an ED generation scheduling that considers environmental objectives has become more important. This increases the complexity of the problem, necessitating a need for a method with high flexibility, which current ED techniques lack.

In a previous paper we had reported on the inclusion of wind power in the ED calculations [9]. The simulation had been performed using a system model with wind power as an intermittent source, and the results of the simulation have been compared to that of the Direct Search Method (DSM) for similar cases [10]. In this paper we report on our continuing investigations into using Genetic Algorithms (GA) for ED for an independent power system with a significant amount of wind energy in its generator portfolio. The simulations were undertaken considering several relevant issues, such as: environmental and economic objectives and several technical constraints such as reserve requirements, ramp rate capability, and transmission limits, as well as different approaches for modelling wind power in ED problems. The preliminary results demonstrate, in line with previous reports in the literature, the effectiveness of GA when measured against a benchmark technique such as DSM. We will also report on the results of the sensitivity analysis that has been performed using the Genetic Algorithm Based Economic Dispatch (GAED) for various load and wind patterns, variations of wind location, reserve requirements, ramp capabilities and transmission limits.

II. ELD MODEL

In this section, the ELD problem of a power system that includes wind generation will be formulated. The paper will use a number of case simulations to investigate the impact of renewable energy (wind power) on the load dispatching calculation. This paper reports on the initial investigations regarding the topic, therefore some simplifications have been made.

The dispatch model in the simulation uses a centralised dispatch in a deregulated power system. Generators in the systems are thermal, wind and diesel. Fuel for diesel generators is assumed to be bio-diesel. Constraints included in the calculation are the maximum and minimum values of generator output, the ramp rate of the generators, and reserve requirements. For simplification, transmission losses are neglected. The economic dispatch process aims at cost minimization subject to these constraints. The flowchart for solving the ELD problems in this paper is shown in Fig. 1.

This paper will use the ELD models suggested by Doherty [6]. Initially, a no wind scenario, as a base case, is used and then a forecasted scenario is also applied. In forecasted scenario, two approaches to deal with wind generators will be applied.

1) ‘Negative load’ approach

This is the simpler of the two approaches, where wind forecast is treated as a ‘negative load’. Therefore, load demand is reduced by the forecast wind power producing a new load demand. This new load demand is then used in the ELD process.

2) Integrated approach

In this approach, wind turbines are included in the calculation. In order to maximise the wind output for the purpose of reducing emission, an artificially very low price (0.01 $/MW) is used for representing wind power.

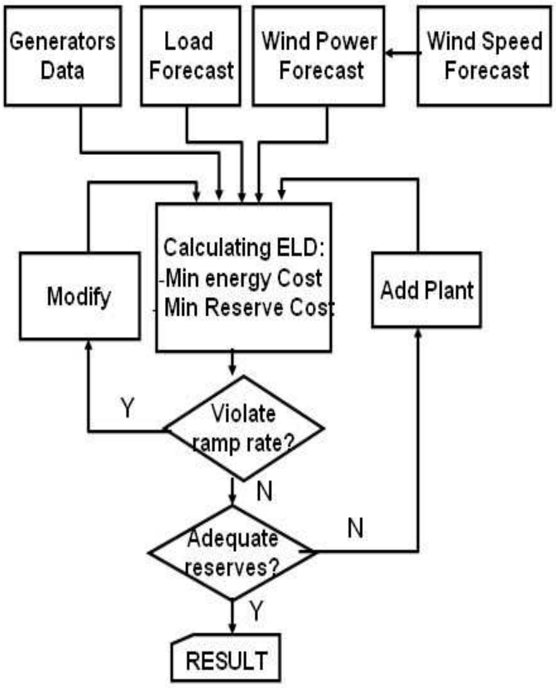


Fig. 1. Flow chart for the ELD problem.

The objective function for the ELD is formulated as follows:

$$\text{Min}\left(\sum C_{pi}P_i + C_{ri}R_i\right), i = 1, 2, ..., N \tag{1}$$

Subject to constraints:

$$P_{load} - \sum P_i = 0 \tag{2}$$

$$P_{i\min} \leq P_1 \leq P_{i\max} \tag{3}$$

$$\left.\begin{aligned} DR_i\Delta t &\leq P_i^{t+1} - P_i^t, \text{for } P_i^{t+1} < P_i^t \\ UR_i\Delta t &\geq P_i^{t+1} - P_i^t, \text{for } P_i^{t+1} > P_i^t \end{aligned}\right\} \quad t = 1, 2, ..., T \tag{4}$$

$$\sum R_i \geq R_{\min} \tag{5}$$

Where:

i, N = generator number, and total number of generators

t, Δt, T = time interval, duration of time and maximum time horizon, respectively

C_{pi}, C_{ri} = the price of power output and reserve of generation i, respectively

P_i, R_i = power output and reserve of generation i, respectively

P_{load} = Load demand

$P_{i\min}$, $P_{i\max}$ = minimum and maximum output of generator i, respectively

DR_i, UR_i = the down ramp and up ramp limit of generator i, respectively

$R_{\min}$= Minimum reserve requirement

Full details of the simulation model used, including pricing and other aspects of the thermal, wind and bio-diesel generation, can be found in [9, 10].

III. SIMULATION RESULTS

A. Cases Studied

Much experimental work was undertaken to determine the most appropriate parameters to use for both the GA and DSM methods for calculating the ELD [11]. The system consists of Thermal generation in the system consists of six generators (P1–P6) with different characteristics. Each thermal generator has both a fuel cost and an emission objective. The generator characteristics were derived from [12]. The wind generation is modelled as a single generator, Pw. The reserve requirements were treated as either a non-linear constraint or included as a penalty factor in the objective function for the ELD. Once these parameters were established several simulation scenarios were undertaken and the results of using GA and DSM for each were compared. An Environmental Economic Load Dispatch (EELD) method was developed which is a multi-objective ELD which combines economic factors with environmental constraints. However, using a static EELD means that there will be no connection between the simulation results from one hour to the next, and hence the ramp rate limit, which compares generator output between successive hours, cannot be included. To include ramp rate constraints a dynamic ELD (DELD) was used based on the work in [13].

Several simulations were then run for various cases with different typical wind patterns (UK and tropical), wind locations, ramp rates, reserve requirements and transmission limits. The results for GA and DSM were then compared. GA tended to provide a better solution than that of DSM, but with higher standard deviation and slower computation time. The reserve constraints were better matched if treated as a non-linear function rather than a penalty factor. For the inclusion of wind power in the ELD calculation the negative load approach tended to provide a better performance than the inclusive approach.

B. Sensitivity Analysis

To investigate the issues arising from the inclusion of a significant amount of wind generation into the power system a sensitivity analysis of the GAED with a negative load approach and non-linear reserve constraints was undertaken for different load patterns, wind locations, ramp rate capabilities and transmission limits.

C. Varying Load and Wind

The inclusion of a significant amount of wind power will lead to more variety in load patterns seen by other generators (net load). The net load will differ from one day to the next based on the varying wind patterns and the other generators' output will fluctuate more sharply to accommodate this effect. In many cases the problem of ramp rate variability can be compensated by the ramp rate capabilities of other generators, without the need for standby generators.

However, under certain circumstances, when the original load pattern fluctuates very quickly at the same time as fluctuations in the wind power, the existing ramp rate capability may not be able to compensate. There are two possible solutions: adding fast standby generators if the ramp rate of the load is positive, which may increase the fuel cost, or by curtailing generation, usually wind generation if the ramp rate is negative, which will lead to wasted wind.

The result of the first option for one particular simulation case can be seen in Fig. 2. In this case the load demand from hour 1 to 5 is very low, and at the same time the other generation cannot afford to reduce their output to accommodate the wind, thus leading to curtailment of a significant amount of wind.

The second option is to shut down one or two thermal generators, as long as the remaining generators have enough reserve, and the wind output forecast is persistently high. In this way the wind output can be maximised and the cost and emissions of the thermal generators can be minimised, although reliability may be reduced. Fig. 3 shows the results of shutting down one generator for a particular simulation case and Fig. 4 is the same scenario with two generators shut down. The graphs show that with one thermal generator off the curtailed wind is much reduced, and with two generators off there is no need for wind curtailment.

D. Dispersed Wind Locations

The effect of wind variability can be reduced by spreading

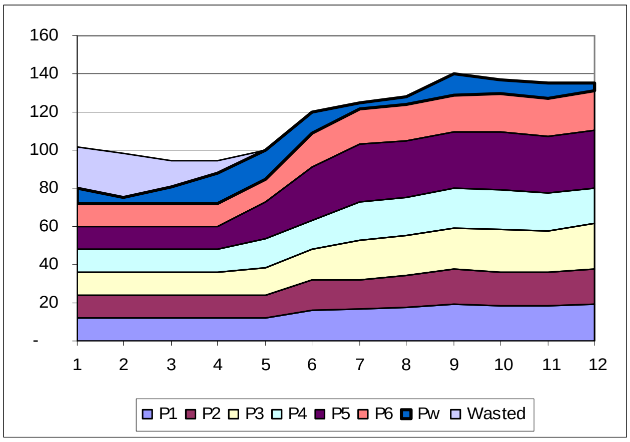


Fig. 2. Generation mix for option 1.

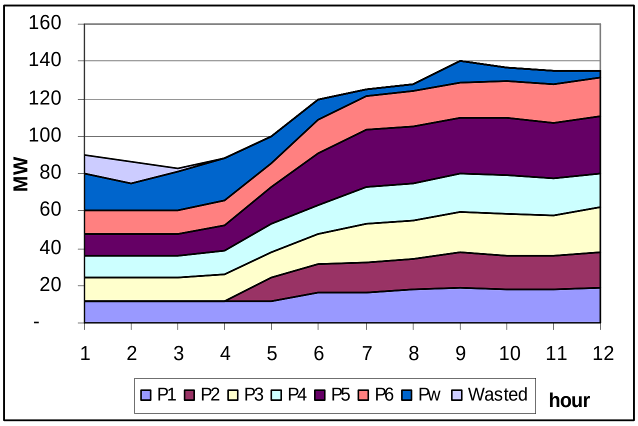


Fig. 3. Generation mix for option 2 with one thermal generator shut down.

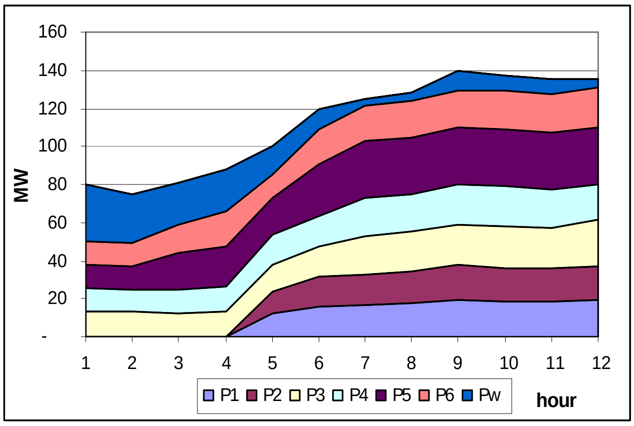


Fig. 4. Generation mix for option 2 with two thermal generators shut down.

the wind generation over a number of locations instead of being concentrated on a single site as they will tend to compensate one another. This effect can be shown by comparing similar systems with different numbers of wind locations (in this case 1, 2 or 3). Each location has a different wind pattern, thus reducing the overall variability. This is indicated by a reduction of the standard deviation for the system as shown in Table I. Therefore, in terms of the ELD problem, the different number of wind locations will change the net load profile, which will be less variable. The results of a particular simulation case with a varying number of wind locations are shown in Fig. 5.

E. Ramp Rate Capability

The ramp rate capability of the thermal generators becomes very important when attempting to compensate for the variability introduced by wind generation. Using the operating and ramp limits for each generator derived from [14] simulations were undertaken to assess the effect of reducing the ramp rate. The results shown in Fig. 6 indicate that the ramp rates were still capable of coping well with the problem without requiring additional back-up generators, even when the rates were lowered by 20%. However, the wasted wind has increased with the lower ramp rates as shown in Table II.

F. Reserve Requirements

It is also important to consider the reserve requirements needed to anticipate both a variation of load and wind forecast error. The correlation between wind power contribution to the total system and the additional reserve

TABLE I
STANDARD DEVIATION FOR VARIOUS NUMBERS OF WIND LOCATIONS

Cases	Standard deviation
System with 1 wind location	8.7
System with 2 wind locations	6.3
System with 3 wind locations	5.7

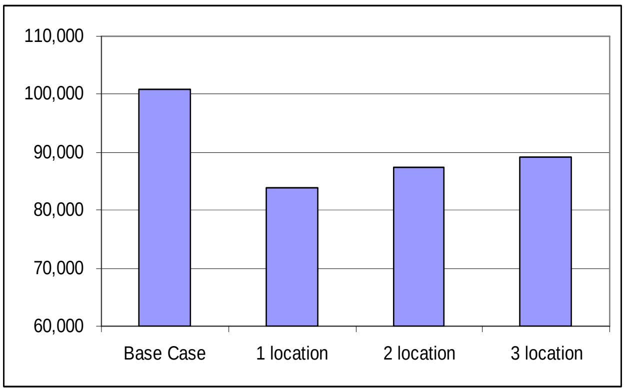
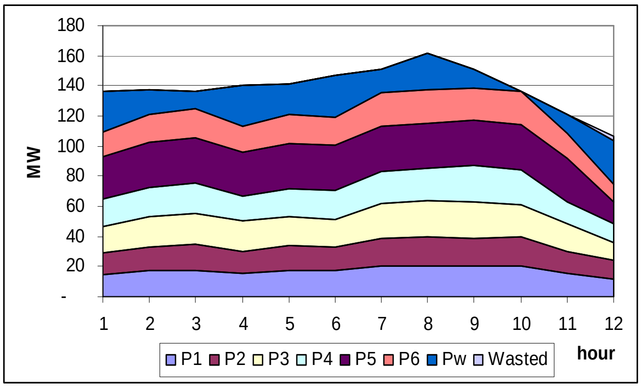
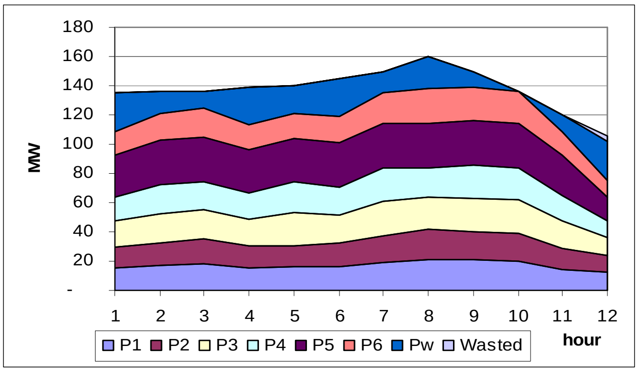


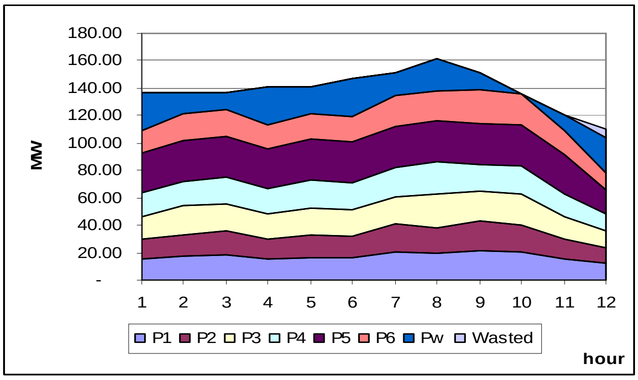
Fig. 5. Comparison of objective values for various numbers of wind locations.



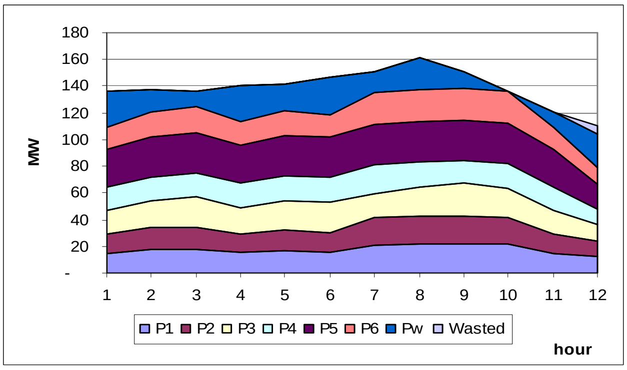
(a). System with 120% ramp rate.



(b). System with 100% ramp rate.



(c). System with 90% ramp rate.



(d). System with 80% ramp rate.

Fig. 6. Comparison of generator mix for varying ramp rate capabilities.

TABLE II

WASTED WIND FOR A SYESTEM WITH VARIOUS RAMP RATE CAPABILITIES

Cases	Wasted wind (MW)
System with 120% ramp rate	2.26
System with 100% ramp rate	3.45
System with 90% ramp rate	6.06
System with 80% ramp rate	6.57

requirements is shown in Fig. 7. As can be seen the additional reserve requirement for 10% contribution of wind power is about 3-5%, which compares with a range of 2-8% as suggested by [15] and [16]. The comparison of the reserve requirements for several cases suggested that the effects of the inclusion of wind are not very significant. Therefore the reserve requirements can be fulfilled by committed thermal generators in all cases without any need for additional back up. Even when increasing the reserve requirement up to three times the total standard deviation, which covers 99.9% possibility of wind variation, the system remains capable of providing the reserve requirements in most of the cases.

However, [17] suggests that there is a necessity of providing “negative” reserves, as well as the “positive” reserves discussed above. Therefore an evaluation was also undertaken using the same criteria as for “positive” reserves and the results showed that “negative” reserve requirements can also be satisfied for nearly all time periods. An example from one particular case is shown in Fig. 8.

G. *Transmission Constraints*

The inclusion of wind turbines can potentially cause problems with power transmission limits. The variable nature of wind turbine output can produce high fluctuations of power transfer to and from areas where wind power is located. To evaluate this effect the simulation system was divided into two areas (A and B) with a transmission line connecting them. Each area had three thermal generators with the wind generators being located in area B. The load in each area was assumed to be the same. Simulations showed that the inclusion of wind power leads to increased fluctuations in the inter-area power transmission, thus this needs to be included in the ELD calculation as an inequality constraint. Simulations for different wind patterns were recalculated with the assumption that the transmission capability limit was 15 MW. A comparison of the objective function value for the system with and without transmission limits is shown in Table III and indicates that the objective function value increases when transmission constraints are taken into consideration.

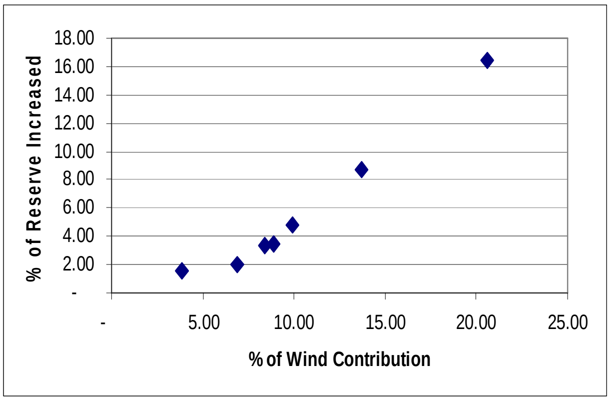


Fig. 7. Correlation between wind contribution to the total system and additional reserve requirements.

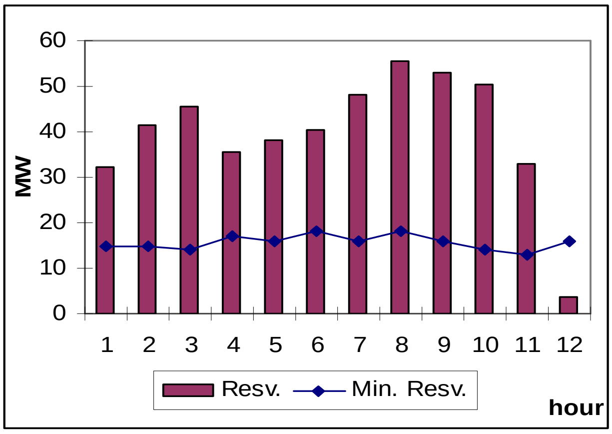


Fig. 8. An example of “negative” reserve requirement and reserve capability.

IV. CONCLUSIONS

Driven by environmental concerns and long-term economical issues, particularly concerning the rise of oil prices, the use of renewable energy has inevitably increased in recent years, and the electrical power industry has become a major player in this area. Therefore the role of renewable energy will become increasingly important to electrical power system managers.

The inclusion of intermittent renewable energy, represented by wind power in these simulations, has lead to additional problems to the power system operation due to the variability and lower predictability of its output. These additional complexities also introduce several implications for the calculation of the ELD, which is concerned with short term scheduling. These include the need to understand wind power characteristics and the consideration of additional constraints such as reserve requirements and ramp rate capability. Two methods of integrating wind power into the ELD calculation have been considered, these being the negative load approach and an inclusive approach.

TABLE III

COMPARISON OF OBJECTIVE FUNCTION VALUES WITH AND WITHOUT TRANSMISSION LIMITS

Cases	Objective Function	
	Without transmission constraints	With transmission constraints
Wind 2.1	83,836	84,142
Wind 2.3	75,891	76,939

A GA method has been investigated for solving ELD for a power system with a significant amount of intermittent renewable energy. The simulations have been performed using a system model with wind power as the intermittent source and the results have been compared to that of a DSM for similar cases. Using the model several conclusions can be drawn from the simulation results as follows:

- Compared to DSM, GA tends to provide a better solution, but with a higher standard deviation and slower computation time.
- Compared to inclusive approach the negative load approach tends to provide better performance.
- The inclusion of a significant amount of wind power will lead to more variation of load pattern seen by other generators (net load) and the net loads tend to be more variable than the original loads. As a result the other generators also tend to fluctuate more sharply to accommodate this variation.
- The variability of wind power can be reduced by distributing the location of the wind turbines, which allows them to compensate for each other and hence reduce variability.
- In general, the ramp rate of the generators can cope well with the problems of variability. However, in some circumstances, when the original load pattern changes quickly and the wind power fluctuates at the same time, the existing ramp rate capability may not be able to compensate. To tackle this problem additional back up generators will be needed or wind curtailment will have to be considered.
- The consideration of reserve requirements is very important in order to be able to cope with variability problem. Besides “positive” reserves, “negative” reserves also need to be taken into account in the ELD calculations.
- The variability of wind power will potentially increase the variability of the power flows to and from the area where the wind power is located, therefore the need to consider transmission limits becomes more important.

In general, the impact of wind generation on the results of the ELD calculation depends on both the characteristics of the system, such as load pattern, the flexibility of the system to cover variability, the reserve capability, and transmission capability, and the characteristics of wind generation, such as the level of wind penetration in the whole system, wind regularity, and the diversity and number of locations at which it is sited.

It is important to note that in these ELD calculations the cost of wind power is assumed to be virtually zero, therefore the real cost of the system will include the cost of wind power. The reason for assuming virtually zero cost for wind power is to maximise its output thereby reducing overall emissions.

Given the increasing complexities of successfully calculating ELD for power systems which are including more and more renewable sources the GAED has shown itself to have the potential of being a very flexible tool for this purpose.

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