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A powerful visualization technique for electricity supply and demand at industrial sites with combined heat and power and wind generation

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Nomenclature

BESS Battery Energy Storage System

CHP Combined Heat and Power

DG Distributed Generation

IRR Internal Rate of Return

MIC Maximum Import Capacity

PCC Point of Common Coupling

PV Photovoltaic

RAPS Renewable AutoProduction Simulator

SEM [Irish] Single Electricity Market

Abstract

The combination of wind generation and combined heat and power (CHP) on an industrial site brings significant design and operational challenges. The stochastic nature of wind power affects the flows of electricity imported and exported to and from the site. Economies of scale favour larger wind turbines, but at the same time it is also desirable to minimise the amount of electricity exported from the site to avoid incurring increased network infrastructure usage charges. Therefore the optimum situation is to maximize the proportion of the site load served by on-site generation. This paper looks at a visualization technique for power flows on an industrial site, which can be used to size on-site generators. The technique is applied to a test case, demonstrating how a simple combined heat and power control scheme can support the integration of on-site wind power. The addition of such CHP control has a small impact on the CHP unit but can greatly increase the proportion of wind generation consumed on-site. This visualization technique allows the comparison of different generation mixes and control schemes in order to arrive at the optimal mix from a technical and economic viewpoint.

Keywords:

Distributed generation; microgrid; autoproduction; renewable energy systems.

1. Introduction

Industrial facilities consumed 18.1% of Ireland's total energy demand in 2009 and represented 33% of the total Irish electricity usage [1]. Historically, such industrial sites have received the bulk of this energy via legacy gas and electricity networks, built around centralized large-scale generation/production plants. The wide-scale development of distributed generation (DG) units, embedded within the network, and sometimes behind the meter, is challenging the centralized model and provides the motive for this study [2, 3].

Certain industrial electricity users may find DG to be a more economical and environmentally friendly method of supplying their energy needs when compared with traditional centralized utility scale power plant supply [3, 4, 5]. DG is placed close to the consumer and in some cases behind the utility meter. Consequently, industrial sites benefit from DG power in three main ways: 1) the ability to utilize heat from combined heat and power (CHP); 2) saving on transmission, distribution and connection charges; 3) fixing a proportion of future energy costs. Additional benefits may accrue from controlling and utilizing excess energy in the manufacturing process.

At present there is a wide range of different DG technologies available for industrial sites. Several studies have attempted to formulate schemes for optimising the operation of microgrids with embedded DG [6, 7, 8]. Hawkes and Leach [7] found that grid-connected DG was generally more economically advantageous than microgrids with weak grid connection, and recommended that a more comprehensive treatment of the economics of renewables in DG environments be carried out. Srivastava et al. [9] used the HOMER model to demonstrate the potential economic benefit of incorporating storage devices into microgrids with diesel generation, but found no economic case for adding storage to microgrids with embedded wind generation. Mohammadi et al. [10] presented a genetic algorithm methodology for optimising the mix of DG units on a grid-connected microgrid participating in a hybrid electricity market which included centralised unit commitment but also allowed limited bilateral trading of electricity. The DG portfolio included photovoltaics (PV), a fuel cell and a battery energy storage system (BESS). The increased flexibility of the hybrid market over the pool market slightly reduced the local economic benefits from DG. In another study of a microgrid with distributed PV and wind generation, a methodology based on mixed-integer linear programming was developed in order to determine the size of BESS in order to maximise the economic benefit under grid-connected and islanded operation [11]. However, it should be emphasised that the results of all such economic evaluations are highly dependent on local subsidy regimes for renewables.

Determining and presenting the optimum DG type, size and mix can be a difficult task for industrial or commercial sites [12,13,14]. Widely varying solutions can be arrived at for two similar or closely located sites. Changing aspects within the site load, such as minimum demand and the duration during which it occurs greatly affect the optimal DG mix and unit size. Taking these options into account and determining the best solution for the site can be a difficult task, because large data sets have to be analysed.

The best approach to complete the analysis is to build a computer simulation model. Numerous existing software models aim to simulate the integration of large-scale variable renewable generation into power systems (see [15,16] for detailed reviews). Tools such as RETScreen, developed by Natural Resources Canada, are aimed at pre-feasibility assessments of renewable energy projects, rather than optimal system design, and operate at coarse time resolutions [17]. Another set of models, such as HOMER [9], is capable of simulating microgrids with weak or non-existent grid connections, or community-scale DG

systems [18, 19, 20]. A survey of over two decades of work on optimising conventional CHP operations is presented in [21]. However, to date the problem of optimising renewable generation in an industrial setting, typically (although not necessarily) with strong grid connection, has not been specifically addressed by any computer model. The Renewable AutoProduction Simulator (RAPS) model has been developed specifically to analyse the supply and demand of electricity on industrial sites and is described in this paper. The model is split into three main modules. The first module calculates the cost of supplying the industrial load from the network. The second module simulates the integration of wind power to jointly supply the site together with grid-supplied electricity. Different turbine types can be specified. Finally, the CHP module can simulate the operation of a range of CHP units. The CHP unit, if selected, is integrated into the remaining site demand with excess power being exported back to the electrical grid.

Increasing the proportion of DG power utilized on-site ensures that the generator receives a higher price for that power, because power exported to the grid will only receive the market export price of electricity, but power supplied directly to the on-site customer displaces the higher grid-supply price paid by the end user. The higher grid-supplied prices are due to additional charges, which are added to the wholesale market price. These extra charges are applied to pay for tax, market operation, supplier's margin and the transportation of electricity from the power station to the site.

The EU Gas and Electricity Directive requires Member States to open their energy markets for large users and distributors [21]. The directive was adopted in Ireland in 2006 with the development of the single electricity market (SEM). The SEM is a centralized wholesale electricity market in which all units of electricity must be bought and sold via a gross mandatory pool. Furthermore the price varies on the half hour as calculated by the market operator's optimisation engine. The engine calculates the price by selecting the cheapest mix of generation units required to meet the full electrical demand on the island of Ireland over the full day. The market engine estimates the price a day ahead of actual dispatch and reconciles the price four days later. This price is made available to industrial electricity users.

Industrial users can decide to fix their electricity price with their supplier over a number of months. The supplier then takes on the risk associated with the price variability. Whether the supplier takes on the risk of the variable market price or the industry site self-supplies, the SEM price is the benchmark price, setting the cost of electricity for each half hour across the island of Ireland. Thus the RAPS model uses this half hour market price to calculate the cost of electricity for the site.

The importance of using the SEM price is its varying nature, giving it the ability to reflect the true cost of grid-supplied electricity each half-hour. There is a high correlation between supplies from different wind farms across the island. It is important to understand that there will be a correlation between the output from DG wind turbines and network-connected wind farms. Due to the so-called 'merit order effect', the wholesale price of electricity is reduced in systems with high wind penetration during periods of high wind generation [22]. Therefore, if on-site wind generation is to be simulated, it should be done using contemporaneous SEM price data and wind speed data. Furthermore the Irish government has specified a target of 40% renewable electricity by 2020, of which wind power is expected to supply a large proportion, forcing down the price of electricity even further during periods of high wind generation [23].

DG units convert different energy resources such as oil, gas, wind, biomass or solar into electricity, heat and motion [24]. To optimize the on-site DG mix it can be helpful to separate the units into two main categories: dispatchable and non-dispatchable sources [24]. Dispatchable DG sources are units which can be called upon to provide power and stability for the electrical system, e.g. CHP, demand side management or storage. A non-dispatchable source can be a slow-response or totally uncontrollable supply, e.g. wind or solar. An overview of an example of such a DG system is given in Fig. 1 showing the factory loads and different supply types.

CHP generation currently meets about 2.4% of Ireland's electricity demand [25]. The majority of this generation comes from units installed at industrial sites, most having a constant heat and electricity demand throughout the year. Typically CHP will require a site with a high and ongoing demand for heat, so that the unit is operational for at least 4000 hours/year [24]. Conventionally, CHP units have been sized to meet the on-site base-load heat requirements with supplementary electricity imported or exported as required [12]. This paper investigates the benefit of changing this sizing and operation methodology. The possibility of picking a smaller size CHP unit and adjusting it to permit the installation of wind DG is considered, therefore reducing the cost of electricity on-site even further than would be possible merely with CHP or wind DG on its own.

Wind generation currently meets about 10% of Ireland's electricity demand. Of this, DG wind power accounts for an insignificant proportion. Nonetheless, industry is increasingly considering wind DG as an alternative or complementary supply source. This is largely due to the fact that a great proportion of the country has relatively high wind speeds. Consequently for these sites, wind power can be an economical option. One such site is Dundalk Institute of Technology in Ireland where a 850kW Vestas wind turbine was installed in 2005 [26]. Taking this concept one step further, the window manufacturing company Munster Joinery installed both wind and biomass CHP two years later.

Investment due diligence was a key step in the above mentioned DG projects, i.e. quantifying possible risks and profits. The task of conducting the due diligence for on-site wind DG can be complicated by the increased risks due to uncertainty surrounding projected wind generation within the project. These uncertainties increase the price of finance and undermine the economics and hence payback. Quantifying these uncertainties is necessary in order to reduce the cost of finance. This is a difficult task, due to the stochastic nature of wind power.

The variable nature of renewable generation from sources such as wind make it difficult to predict and model, as patterns may only emerge over a long time frame, requiring large data sets. The visualization techniques proposed in this paper can represent these large data sets in a single plot. This graph then gives a clear picture of the benefits wind power can bring to consumers, demonstrating that wind power can be beneficial during a very high percentage of its operating time, if sized properly. These techniques reduce uncertainties within the design process of distributed wind generation; conveying a clear picture of the issues being faced. Additionally the technique shows that dispatchable units like CHP can be adjusted to help integrate larger wind DG units, by reducing export to the national grid. Furthermore controlling the CHP in this manner can reduce the overall price of electricity for the industrial user.

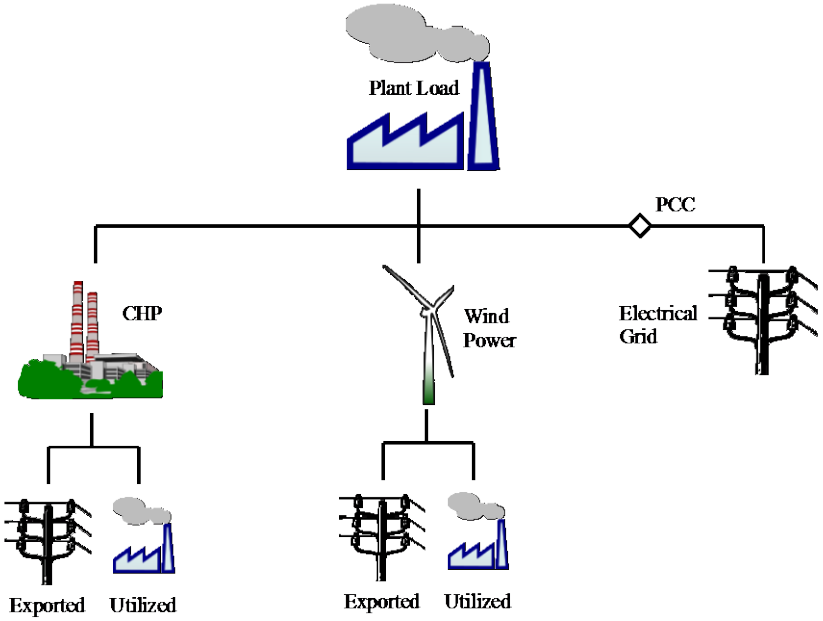

Figure 1. Renewable autoproduction simulator model overview.

The main objective of the paper is thus to put forward a novel visualization and analysis technique, which is then used to illustrate the added benefits achievable by controlling CHP units to accommodate the combined use of wind generation and CHP, thereby economically supplying more of the site load. The analysis is carried out using the RAPS techno-economic model developed by the authors for simulating industrial autoproducers on gross mandatory pool markets such as the Irish SEM.

2. Modelling Approach

2.1 Model Structure and Data Flow

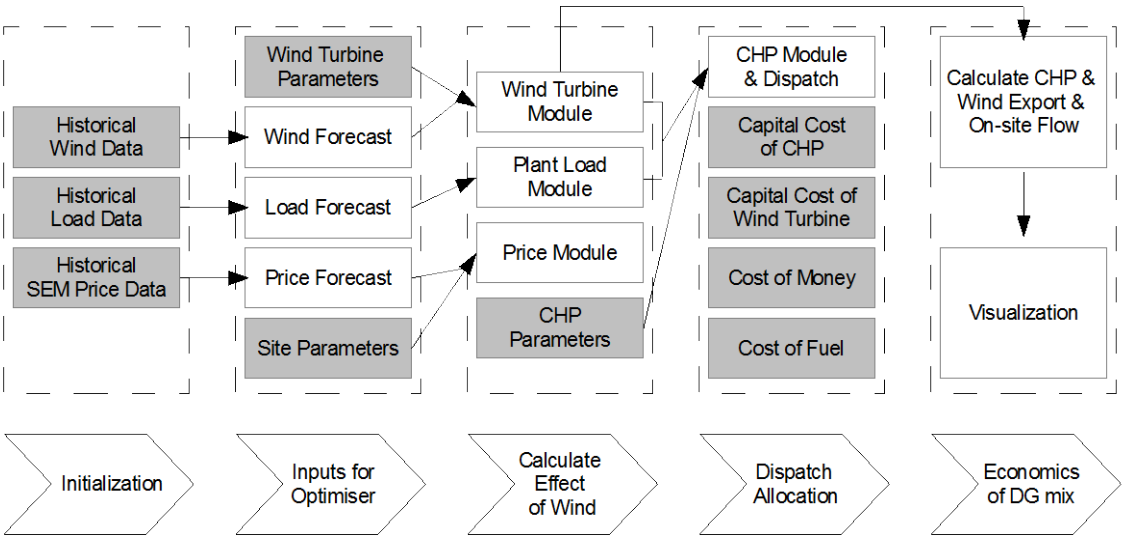

Figure 2. RAPS model structure and flow

Fig. 2 gives the structure and flow of the RAPS model: blue indicating where data input is required; yellow indicating processing stages; the green boxes show the distinct steps taken when analysing energy supply and demand at an industrial site. The process flows from left to right, with the data being utilized within the modules shown, returning a site-specific DG evaluation for the factory or industrial unit.

Initially, recorded data is loaded into the model and converted to ten-minute intervals. This data is then used to forecast future data values. Following the generation of the wind forecast, this wind speed value is converted into electrical generation data using the wind turbine module. Subsequently, the load and SEM forecasts are multiplied in the load module to set the on-site cost of power. The process within these modules is further detailed in the following subsection. The next step combines the wind and load module to calculate the flow at the point of common coupling (PCC), the point where the on-site network meets the grid. Then, the CHP module is simulated with the unit being dispatched using specific control algorithms. Now the user can pick and choose different scenarios, which are then evaluated and visualized by the model.

RAPS is a pre-installation economic feasibility assessment tool which also has the unique capability to incorporate operational strategies in its calculations, in order to arrive at more realistic results. For economic assessments it is important that the capital costs of the units are included in order to determine if investments in the units are justified.

2.2 Modelling on-site generation

The RAPS model calculates the cost of a range of options to supply electricity to an industrial site. The Matlab simulation environment (Mathworks, USA) was used to construct the model. The first modelling step is to create the network electricity supply. Subsequently, wind power is simulated and integrated into the grid supply, followed by CHP, incorporating a simple control scheme, thereby helping to integrate all three options achieving the lowest cost of electricity for the site. The model simulates the flow of electricity at a ten-minute interval over a full year. To do this, concurrent time series data is required for the factory's electricity load, the wind speed and the SEM market price. All data sets are converted to a ten-minute resolution primarily because wind speed data is normally provided at this resolution.

The cost incurred by a site for importing electricity, and the revenue earned by generators for exporting are calculated by multiplying the import and export levels in kWh by the unit price for electricity at that time. The wholesale market price (i.e. the SEM price) is used as the unit price required in completing these calculations. The SEM price is considered within the model to be the benchmark electricity price. The value of electricity used on-site is calculated by multiplying the SEM price for the particular trading interval by the corresponding kWh electricity value. Additionally, network use of system charges and fixed charges are applied to imported electricity. These additional charges, which are added on top of the SEM price, make it more attractive to consume electricity generated on-site, thereby displacing grid imports, rather than exporting it to the grid. Equivalently, the value to the site of electricity generated on-site is higher than the price achievable for exporting electricity.

The operation of the cost model may be described by the following equations:

$$D_{site}(t) - G_{site}(t) - I(t) + E(t) = 0 \qquad \textit{(eqn. 1)}$$

$$C_{import}(t) = I(t) * (P_{SEM}(t) + N(t)) \qquad \textit{(eqn. 2)}$$

$$R_{export}(t) = E(t) * P_{SEM}(t) \quad \textit{(eqn. 3)}$$

where $D_{site}(t)$ is the site gross electricity demand at trading interval t, $G_{site}(t)$ the corresponding on-site generation, $I(t)$ grid imports, $E(t)$ grid exports, $C_{import}(t)$ the cost of imports, $P_{SEM}(t)$ the wholesale unit electricity price, $N(t)$ represents the network and use of service charges, and $R_{export}(t)$ the revenue from exports. Eqn. 1 implies that on-site generation, demand, import and export must be in balance for each trading interval. From Eqns. 1-3 and Fig. 1 it can be seen that if both $D_{site}(t)$ and $G_{site}(t)$ are non-controllable, then $G_{site}(t)$ should always be used first to satisfy $D_{site}(t)$ in preference to exporting, in order to displace more expensive imports. If D_{site} is flexible over several trading periods, it may be possible to schedule site demand in such a way as to displace even greater levels of imports with on-site generation, thereby reducing overall net costs [27].

At this point it is important to differentiate between entirely grid-connected DG and on-site DG; the latter is in fact also grid-connected but located on-site at the factory side of the electrical meter. On-site DG supplies electricity directly to the factory loads. This power does not participate in the electricity market if it does not leave the site and does not flow through the network operator's meter. However, excess on-site DG electricity may be exported to the grid. Export happens only if the factory loads are at a lower level than the generation output. This is of particular importance to the economics of on-site DG, because on-site DG units will effectively receive a higher price for electricity that is consumed directly by the factory, displacing end use electricity and treating said price as the DG electricity unit price. The end use price is higher because the end user pays additional charges, which are added to the SEM price.

Exported electricity will receive the market price, similar to grid-connected wind farms or power stations. Typically, there is as much as a 40% difference between the end use price and the export market price. This difference is the main driving factor for the installation of on-site wind DG. Large thermal power stations and wind farms have economies of scale, and wind farms usually have higher mean wind speeds than wind turbines located on industrial sites. However, on-site DG may be economically competitive as a power source as it can supply local loads at lower cost than the centralised alternatives. This is due to the fact that power is being used directly at the site and doesn't have to travel through the network or the market. The disadvantage of centralized generation passing through the network is that the total network costs are socialized across all end users. This discourages efforts made by the user to locate and balance DG units close to the site, and favours the location of DG within the site itself [28]. For the purposes of economic optimisation, the lower costs associated with on-site generation can be considered equivalent to a higher "price" obtainable for this type of generator to serve the site load, compared to a remote power plant.

Furthermore, CHP can compete with centralized power generation due to local capacity to use the heat output. It should be made clear that DG and its larger network equivalent (power stations or wind farms) are strongly coupled through the market. Therefore, it is important for DG units to maximize their advantages. For CHP the advantages are: the use of waste heat in the factory processes; and the higher price (lower cost) commandable for electricity produced on-site. For on-site wind DG the only advantage is the higher price payable on-site for this electricity. This price must be received for a large percentage of the power generated in order for the turbine to be able to compete with grid-supplying wind farms. The only way this price is received is if there is sufficient plant load available for the turbine to supply.

2.2.1 Plant Modules

The plant load module calculates the cost of the site's electricity if it was to be supplied completely by the utility grid. The module reads in metered electrical consumption data for the site on a half hour interval over a full year. This data is then converted to ten-minute time intervals and multiplied by the appropriate site prices and fixed charges. The prices and fixed charges are selected according to the site's maximum import capacity, maximum export capacity and distribution group. Both fixed and variable charges are applied and full cost of electricity on-site is calculated over the full year.

The price and costs module reads in the fixed and variable components of the electricity price charged to Irish industrial sites. The SEM price is the variable component, and the module also holds a database of the fixed Irish market charges. These charges are applied according to market rules for both consumption and DG.

2.2.2 Generation modules

Each DG unit is simulated using the specifications from the DG manufacturer's data sheets. The specifications give minimum load, power curve, rated power and shut down level. These specifications are then saved creating a list of DG units. These DG units can be selected to supply the factory load, with the effects being presented graphically on-screen

The wind module reads in raw wind speed data measured at two heights from a wind mast and converts it into electrical power. The wind speed data is first converted to turbine hub height wind speed data using the log law. The power curve equation for the specified wind-turbine is then utilized to calculate the generated power. This simulated turbine electricity is then subtracted from the site load calculating the percentages of generation that would be utilized on-site and exported to the utility grid. This reduces the cost of grid electricity as the load is partially or fully supplied by the turbine. These savings along with export revenue is passed on to the turbine module, which is used to determine its internal rate of return (IRR). Having arrived at the turbine with highest IRR a series of CHP units are also simulated.

The CHP module acts in a similar fashion, with the manufacturer's power-to-fuel curve being used to calculate the cost of generating electricity. With CHP generation the optimum generation level is calculated according to the CHP control algorithm specified in Fig. 3. The CHP output is then added to the combined wind and load modules and the flow at the PCC is estimated. Here again the module specifies appropriate prices for export and on-site supplied electricity, the value to be received for electricity is calculated.

The value received for electricity plus a fixed value for heat is subtracted from the cost of fuel used in the generation process giving the revenue streams for the CHP unit. The exported and consumed on-site electricity charges become the revenue used to calculate the IRR for the CHP.

2.2.3 CHP Dispatch Algorithm

The CHP algorithm displayed in Fig. 3 has been designed to curtail the CHP unit to allow wind to take precedence over the on-site electrical load. This paper uses a basic algorithm described in [29] as the main focus of the paper is on the visualization technique being proposed. This simple algorithm adjusts the CHP unit by first forecasting the wind speed and site load over the subsequent ten-minutes. The forecast is then used to determine the expected export level at the PCC. Having determined the export level, the CHP unit is then adjusted

between its rated output and minimum run level, thus reducing the export and increasing the viability of a dual DG system.

3. Analysis and visualization technique

The issue of balancing grid scale wind power on the wider utility grid has been previously studied (e.g. [30]). However, as DG is increasingly integrated into industry and domestic houses, the importance of selecting and sizing appropriate units needed to be communicated to the general public. With the help of visualization the benefits of adding and controlling DG units become clear [31]. This approach gives a concise set of graphs, which help the user make a more informed decision on the best option for a given site.

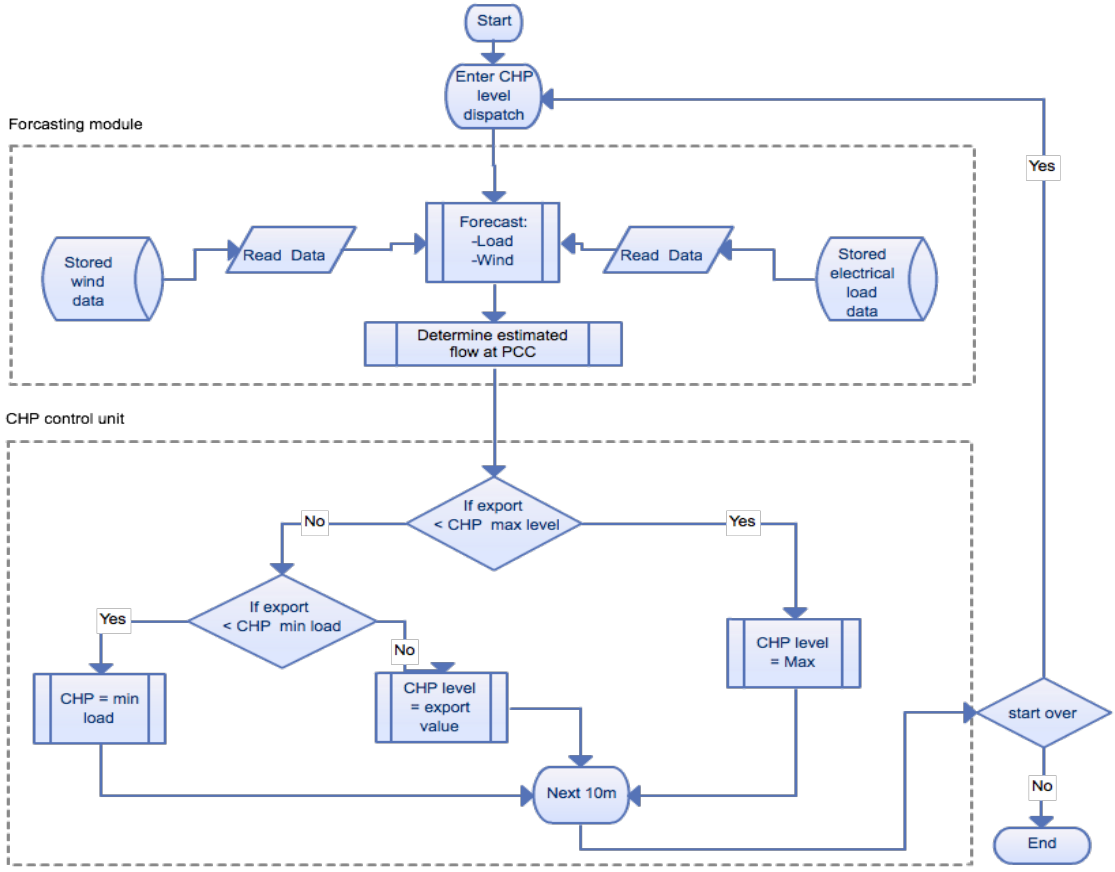

Figure 3. CHP dispatch algorithm to accommodate on-site wind generation.

Frequency distribution plots are the basis of the visualization method proposed in this paper. This technique shows that with careful consideration an optimal site DG mix can be arrived at, with the aid of the visualizations. The following section explains how these visualization graphs are generated based on a specific example. This visualization technique is then used in the results section to establish the DG integration issues for the particular site.

3.1 Visualization of time series data

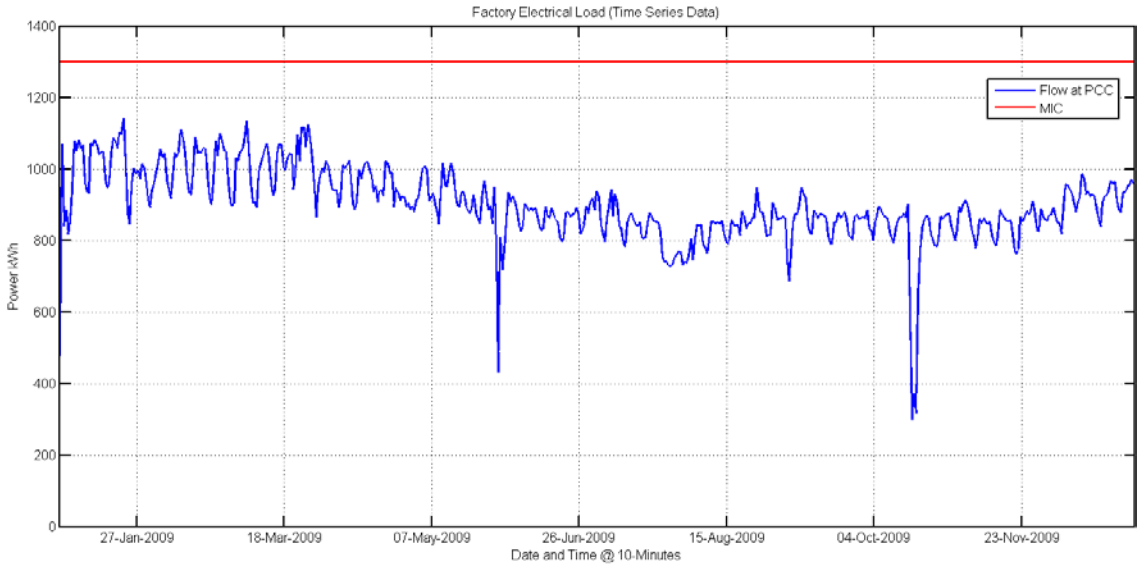

Figure 4. Time series of electrical flow at the PCC

Fig. 4 shows the electrical consumption for a notional case study site over one year. Wind generation and demand time histories were based on actual datasets recorded from a single 850 kW turbine, and an industrial plant with a maximum load of approximately 1300 MW. The blue line displays the site load, showing its periodic nature. This is typical of most industrial units with weekly, daily and annual patterns. Furthermore the factory shutdown period, in November, is noticeable with the dip in electricity consumption. A data fault is also visible in June; this is due to either an error in data, or a blackout on the grid. It is difficult to determine from this plot how often the site load drops below a certain level, a value necessary to select the optimum turbine size. Additionally it is impossible to establish the quantity of energy being consumed at different power levels. This can be seen more clearly when the time series data is transformed into a frequency distribution plot.

An informative picture of the electrical power flow patterns at the PCC is presented in Fig. 5, giving a simple demonstration of this visualization approach. Fig. 5 gives the same electrical load data presented in Fig. 4 but the data is now converted into two frequency distribution graphs plotted on the same axes. The solid line represents a distribution of percentage of the time the turbine is generating at a particular level and the dashed line represents a distribution of the percentage of electricity it generates at that level.

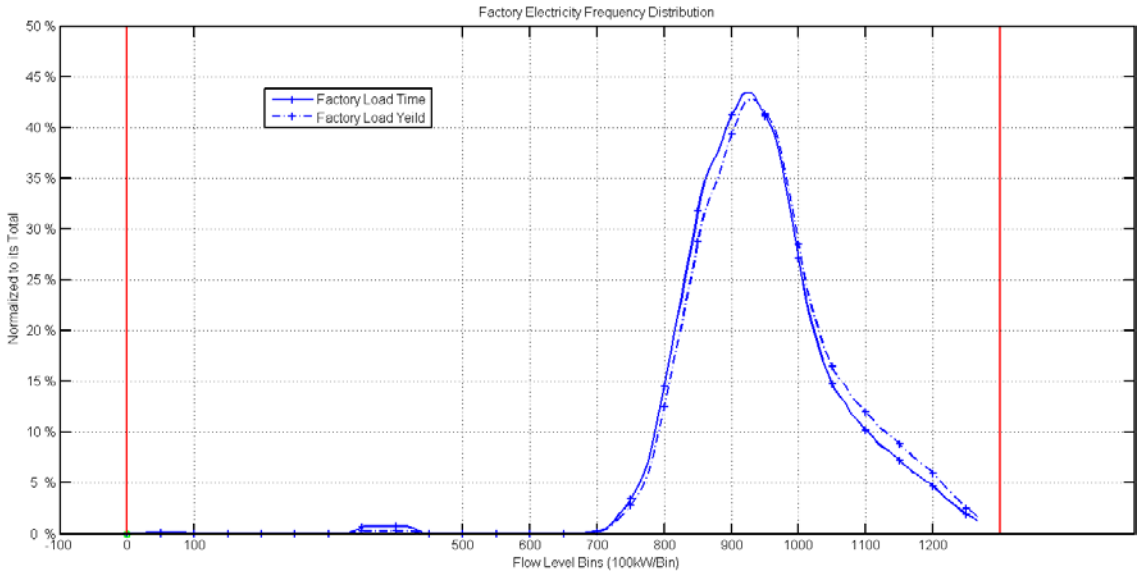

Figure 5. Frequency distribution of site electrical flow at the PCC.

The dual representation of percentage time and percentage electricity is displayed using the same y axis. The x-axis represents kW power level in frequency bins. This gives an instant representation of the expected electrical flow levels at the PCC. The real benefits from this form of visualization will come when the plant load, CHP and wind power are integrated, and this is given in the following section.

4. Results

4.1 Wind, Load and Flow at PCC

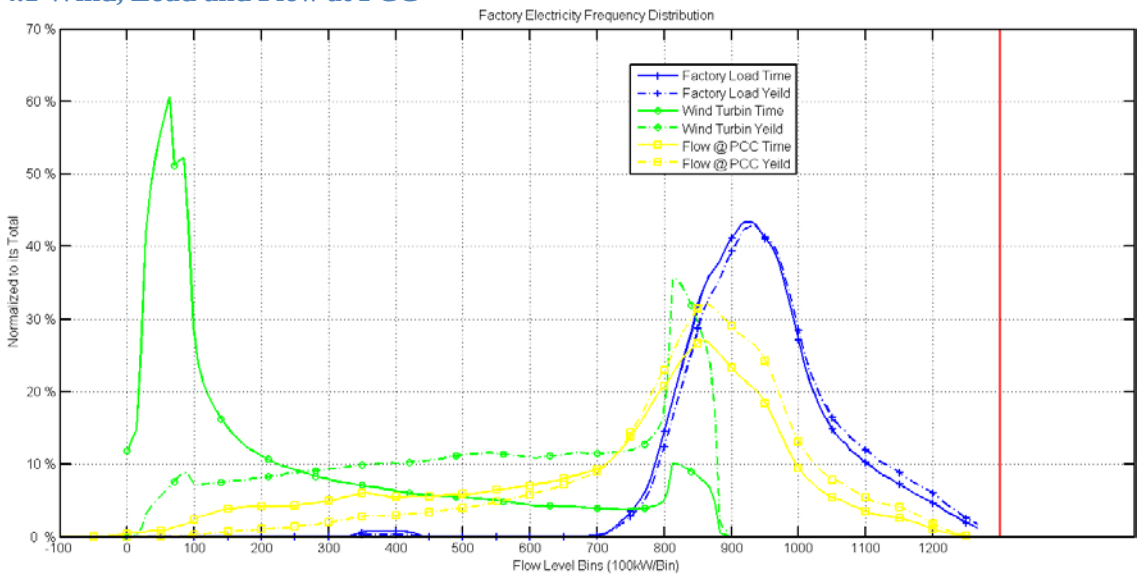

Figure 6. Frequency distribution showing wind, load and flow at the PCC.

Fig. 6 presents the frequency distribution of electricity at the site with wind generation installed. The frequency distribution displays the percentage of time spent within each 100 kW bin, indicated by the solid lines. The dashed lines illustrate the percentage of total energy yield falling within each particular bin range.

In Fig. 6 the wind turbine output spends approximately 40% of the time (solid green line) at an output level of 0 -100kW. This is intuitive as there can be long periods with no wind, consequently the turbine will not generate power. As a result, the yield distribution (dashed green line), shows that just 5% of total yield occurs within this range. Therefore, the plot succinctly illustrates that wind generation at the site will be zero or negligible for 40% of the time. This may seem to mitigate against employing wind DG at this site, but it is also visible from Fig. 6 that the turbine produces 20% of its overall energy yield near its rated power output of 850 kW.

4.2 Wind, CHP, Load and Flow at PCC

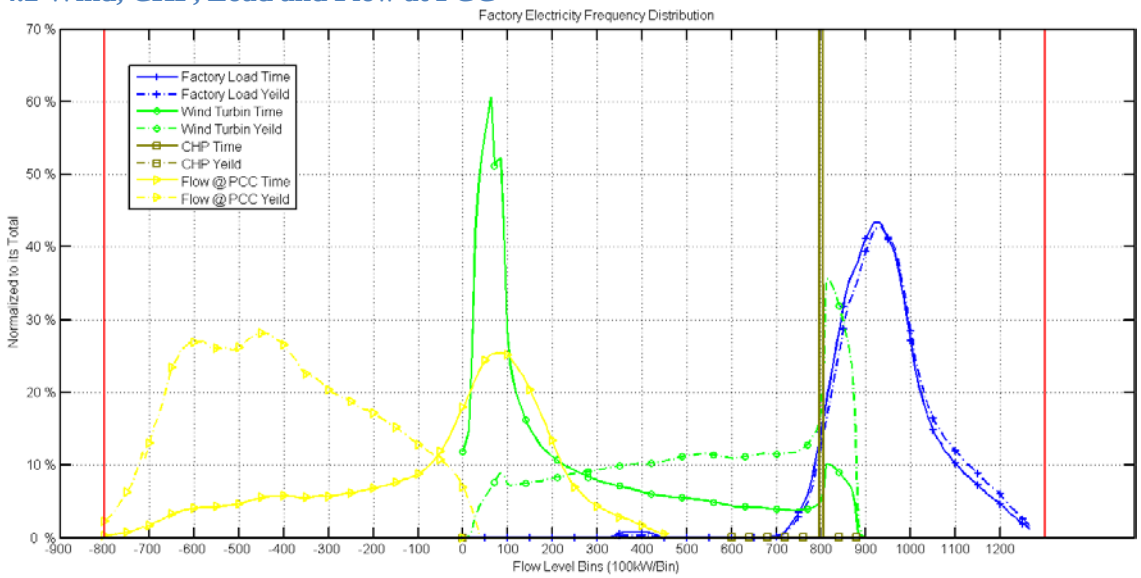

Figure 7. Frequency distributions of CHP generation, wind generation, load and flow at the PCC.

Adding CHP to the previous DG supply scenario (Fig. 7) shows that a large percentage of the yield is exported to the utility grid, illustrated by portion of the distribution of the PCC flows on the negative side of the *x* axis. It can be deduced from this that a large size energy storage device would be necessary to avoid these exports. At the same time, the PCC flow distribution indicates that such a storage system would be utilized to its maximum only a fraction of the time, which would likely make its capital cost unrecoverable. Taking these findings on board, initial results indicate that adjustment of the operation of the CHP unit may be an economical alternative to energy storage in this case.

4.3 Wind, regulated CHP, load and flow at PCCs

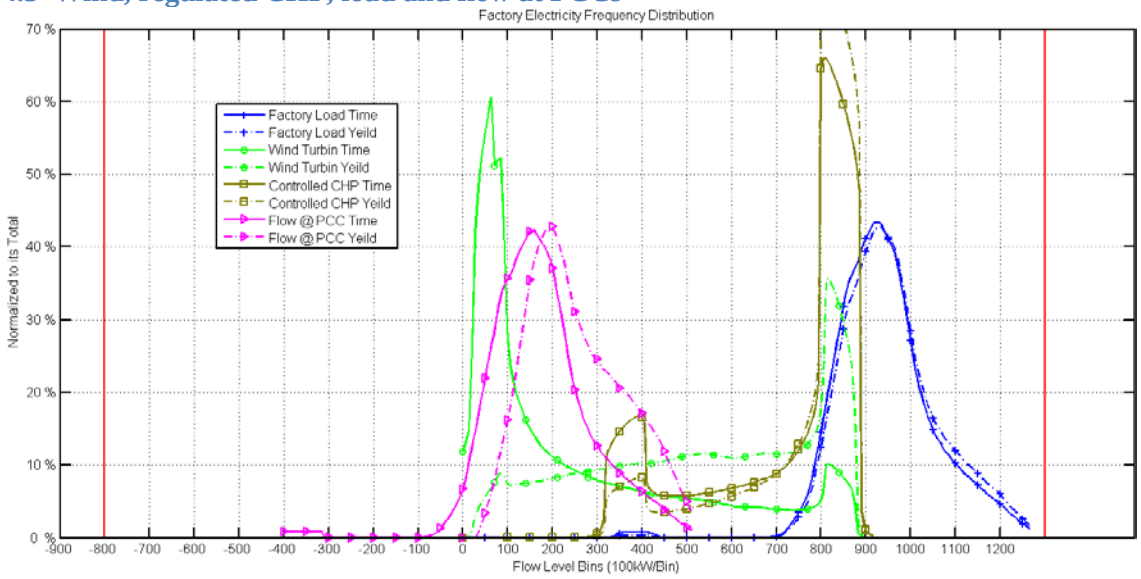

Figure 8. Frequency distribution of CHP generation, wind generation, load and flow at PCC with CHP control.

Fig. 8 adds the effects of one of the possible CHP control schemes to the test site. The proposed scheme is well within the operation limits of the CHP unit, and simply involves regulation of the CHP output in response to fluctuations in site demand net of wind generation. A reduction in export flows is instantly clear. The amount of time spent exporting and the percentages of energy exported have been reduced. No provision has been made to reduce import flows.

Fig. 9 combines plots from Figs. 7 and 8, magnifying export flows at the PCC. It can be concluded from this graph that downward regulation of the CHP would reduce the size of any required storage device [31]. The CHP unit would be curtailed for a minimal amount of time. Adjusting the CHP operation will reduce its life; however the savings achievable should be able to offset this. Moreover the algorithm allows for a larger wind turbine, permitting greater economy of scale. The combined extra cost of the heat load in curtailing the CHP unit may be marginal [32]. The fact that there is a corresponding reduction in fuel costs, then actual savings lost during these short periods are outweighed by the improved larger turbine with a higher percentage of its yield used on site. In an experimental system involving a microgrid with multiple embedded DG units, a combination of day ahead scheduling and real time rescheduling was observed to reduce operational costs by 8.5% [33] which is consistent with the potential savings identified in this study. It should be noted that, depending on the site heat demand, the output of the CHP unit may not always be controllable to the extent implied here, however this example serves to illustrate the potential benefits of CHP control. In [34] a scheme is put forward to co-optimise heat and power in a CHP system, and in [19] several approaches to optimisation of CHP systems operations are reviewed and it is noted that multi-objective optimisation schemes, such as combined optimisation of electric power, heat and costs are still relatively rare.

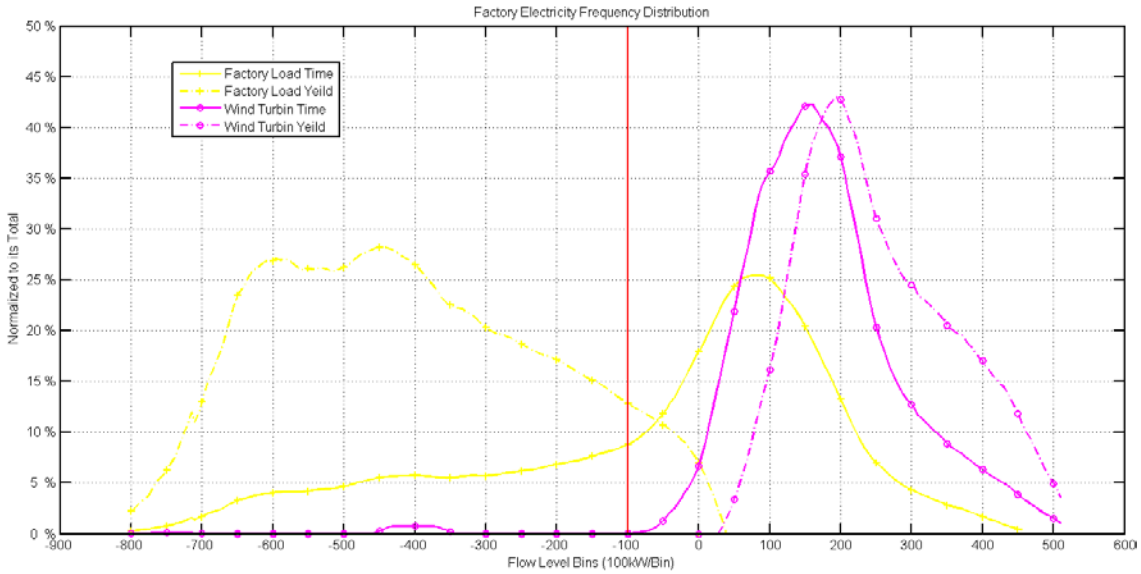

Figure 9. Focus on the effects of implementing a CHP control scheme on flows at PCC

5. Conclusion

This work has shown that careful consideration needs to be used when installing a mix of DG units at industrial sites. There is a need to investigate the optimum mix of generation types as well as the appropriate size for each unit. Current and possible future site load is a major driving factor when determining the mix and size of the units. An additional consideration when picking and sizing the mix of units is that possible control schemes for dispatchable site generators should be part of the overall analysis, as implemented in the RAPS model presented here.

The results clearly highlight that the maximum economic benefits for on-site wind generation are attained when combined with a controllable CHP unit of the right size. This is of vital importance for sites with large heat loads considering the installation of CHP. Further investigation into the development of optimum control schemes is essential, taking all energy sources into consideration. There is a need for industrial modelling software in this area capable of creating and comparing scenarios with different CHP dispatch and control schemes. The model and visualization approach presented in this paper can be used to identify and economically assess such control schemes.

The major issue facing the development of possible software solutions is the variety of potential DG systems, which are locally optimized for each site at each geographical location. The utilization of available fuel sources is very location-dependent, so the developers of on-site micro-grid software need to incorporate this. There is a need for software which has the ability to use streamlined graphical analysis while accurately representing the technical capabilities of the various DG units. Future modelling work will concentrate on incorporating the constraints posed by non-flexible heat demand on the CHP power output.

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