University of Strathclyde

Additional Wind Generation Connection to the Shetland Power System

July 2006

CONTENTS

1. Background

1.1 The Shetland Electricity Network

The electricity network in the Shetland Isles is a true electrical island, with no connection to the main transmission system in Great Britain. The network consists of three 33kV circuits emanating from a hub at Lerwick, together with 11kV and low voltage circuits from the core 33kV system. The two northern 33kV circuits can be reconfigured by means of normally open points at their points of mutual interconnection. The 33kV network is shown schematicallt in Figure 1 and geographically in Figure 2.

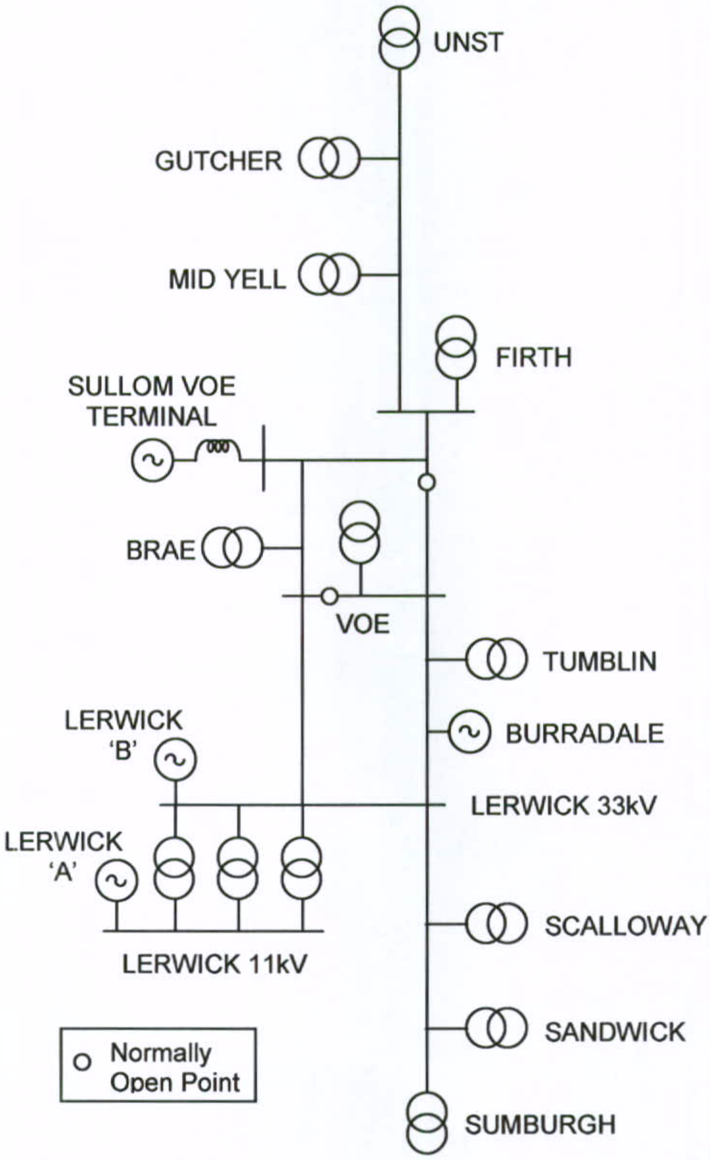


Figure 1: Shetland 33kV network

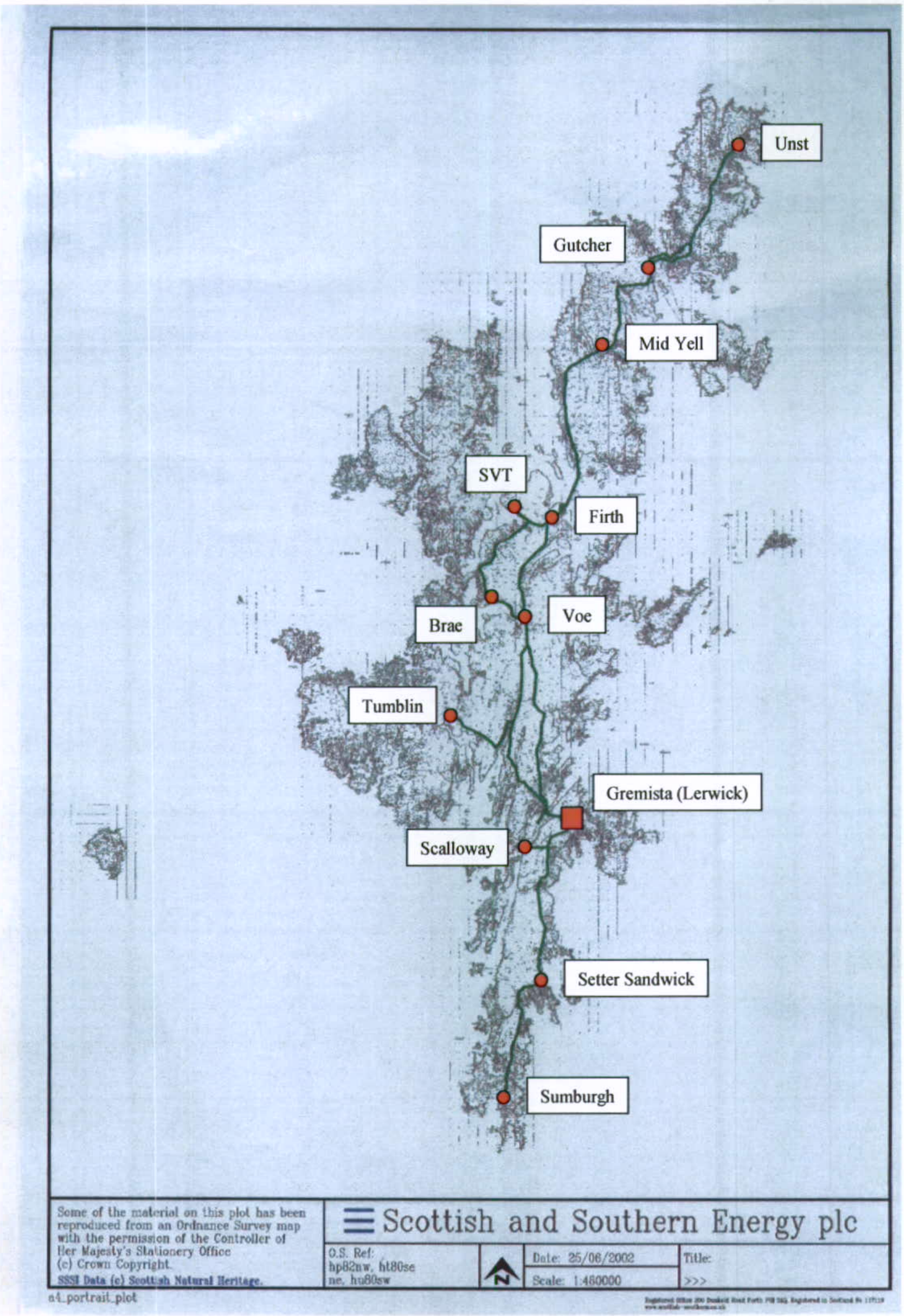


Figure 2: Geographical plan of Shetland 33kV network

Generation is located in three places:

- Scottish & Southern Energy own diesel generators of varying individual unit sizes at Lerwick Power Station (LPS). Lerwick units are divided into two separately located groups. Older units are located in the "A station" while more recent units are located in the "B station". Lerwick is at the hub of the distribution network, but is geographically towards the south of the Shetland Islands. Lerwick generators and capacities are shown in Table 1.

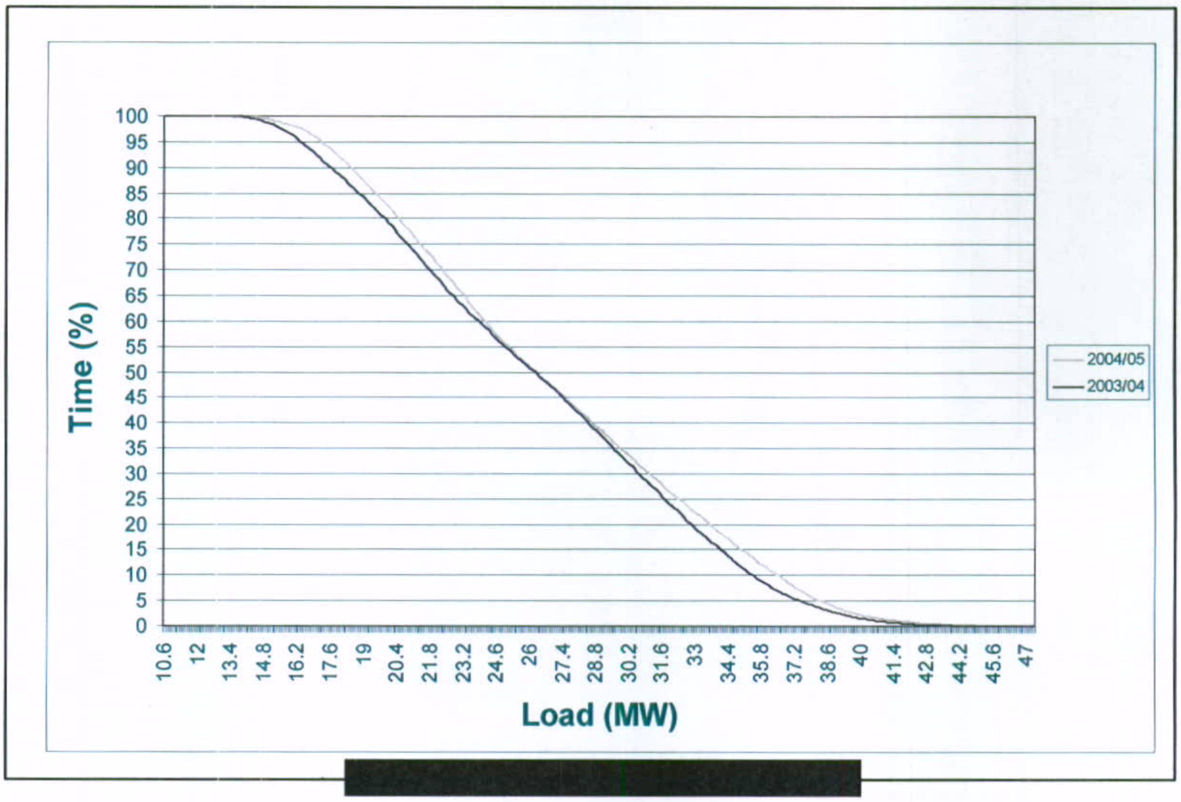
Unit Number	Station	Prime Mover	Rating (MW)
3	A	Diesel engine	4.6
4	A	Diesel engine	4.6
5	A	Diesel engine	4.6
8	A	Diesel engine	3.5
10	A	Diesel engine	4.6
11	A	Diesel engine	4.6
13	A	Diesel-fuelled gas turbine	4
14	A	Diesel-fuelled gas turbine	4
21	B	Waste-heat steam turbine	2
22	B	Diesel engine	8.1
23	B	Diesel engine	8.1
24	B	Diesel engine	12.75

Table 1: Lerwick generating units

- Independently-owned relatively large gas turbine generators at Sullom Voe Terminal (SVT). Sullom Voe is towards the north of the islands. SVT has three gas turbines; export to SSE is constrained to 22MW (winter) or 18MW (summer) by circuit ratings.
- An independently-owned windfarm at Burradale, close to Lerwick Burradale has three 660kW generators and two 850kW units for a total capacity of around 3.7MW.

As an electrically islanded network, all variations in system demand must be met by these three generating stations. Maximum Shetland demand is approximately 50MW and minimum demand is approximately 14MW. There is a significant element of concentrated load, including a large fish factory. This industrial demand includes a significant induction motor load.

[redacted]



[redacted]

[redacted]. For 95% of the year, Shetland demand is at or above the 16-17MW level; for 90% of the year the demand is at or above the 17-18MW level. In both cases, the most recent year is at the higher end of the range. Total Shetland energy demand in 2003/04 was 232GWh; in 2004/05 it was 236GWh.

In the analysis presented here, the more recent data for 2004/05 will be used.

1.2 Current Operations

The Shetland network is operated from a control room at Lerwick. The principal challenge facing the operators is in meeting the varying island load with the best combination of the three sources listed above while respecting system constraints.

Required SVT output is nominated by SSE to the generator operator on a day-ahead basis. [redacted]

[redacted]

[redacted]

[redacted]

Within the constraints of the contract and of the power system, SSE aim to maximise the output taken from SVT in order to reduce the generation at Lerwick on economic and engineering grounds.

Except under outage conditions, two SVT generators will operate at all times in order to provide security to the on-site power supply fed from these units. Two technical constraints apply to SVT export to the SSE network. As previously noted, the circuit connecting SVT to the SVT network constraints SVT output to 22MW in winter and 18MW in summer. A second constraint is maintenance of voltage stability in the Shetland network. At present, this requires that no less than 50% of the demand is met by LPS at all times. SSE is currently procuring reactive compensation equipment which is expected to reduce the proportion of Shetland demand which must be supplied from LPS to 40%. The operation of this compensation plant will be assumed in the analysis presented in this report.

Output from Burradale is not controlled by SSE. Depending on the availability of wind turbines and the wind conditions, Burrdale may produce anything between zero and its full rated output, and the output may vary significantly in response to changes in the wind.

[redacted]

1.3 System Performance

Daily load profiles for two days in spring 2005 and winter 2006 are shown in figures 4 and 5 below.

[redacted]

Figure 5: Load and generation profiles for 12 January 2006

It can be seen that the demand profile is characterised by a number of large steps ranging in size up to 7-8MW as a result of teleswitching, which occurs over the full 24 hour period. [redacted] Since the demand steps are highly predictable, they can be balanced through planned adjustments to the output of LPS including starting and stopping units, as well as through governor action at SVT.

[redacted]

The operational regime at LPS depends on load conditions. Since there is an aspiration to extend the life of LPS units by reducing their accumulation of operating hours, short peaks in demand are likely to be met by SVT. Since longer peaks might incur a more significant penalty cost, it is more likely that an LPS unit would be started. Maintenance of voltage and voltage stability is a more important driver of LPS unit use; diesels will be started if required to provide voltage support. Typically, operators would expect to see three or four starts and stops of A station generators in a day.

1.4 Demand for New Wind Connections

There is existing demand for the connection of new wind generation on Shetland. SSE has received proposals for the connection of [redacted] Further proposals may be forthcoming if it can be shown that additional wind generation output can be reliably accepted by the Shetland distribution network.

1.5 Possible Connection Frameworks

Three possible connection frameworks might be applied to new wind generation developments. Under a **firm** connection framework, a generator would be permitted to connect and run at any desired output under all circumstances, including a first contingency which does not isolate it from the main Shetland network.

Under a **non-firm** connection framework, a generator would be permitted to connect and run at any desired output under normal circumstances, but would be required to accept automatic disconnection or an instruction to promptly disconnect under specified outage or contingency conditions. No compensation would be payable for output lost though such disconnection.

Under an **actively-managed** connection framework, a generator would be permitted to connect subject to its maximum output at any time being restricted by the network operator – with a lower limit of zero – to the maximum which could be accepted by the system without loss of supply security, power quality or interference with the contractual rights of generation developments which predate the active management scheme. Available capacity for actively-managed output would be divided amongst such generators in an agreed manner. No compensation would be payable for output lost as a result of such a restriction on generator output.

2. System capability for wind connected on a firm basis

2.1 Burradale Connection and Operation

The existing windfarm at Burradale is connected to the Shetland network on a firm basis. Burradale's connection was made on the assumption that in the event of loss of the wind farm, the maximum acceptable transient frequency drop would be 1Hz (2%) rather than the 0.5Hz applied on the mainland power system. For consistency, the figure of 1Hz has been adopted for the studies described in this report.

SSE has no operational control over the operations of the Burradale generating units in terms of day-by-day connection and output. [redacted] Additional wind developments might be expected to exhibit [redacted] volatility in output.

[redacted]

[redacted]

2.2 SVT and LPS Operational Restrictions

In addition to the contractual framework described above, SVT output is restricted by circuit capacity to a maximum of 22MW in winter and 18MW in summer. SVT operation at very low output is discouraged; there is a risk of SVT's export to SSE being tripped by reverse power protection applied to the SVT connection to SSE. [redacted]

Operating LPS diesel generating units are required by emission constraints to run at a minimum output of 80% of rated capacity. Significant demand for reactive support from LPS units can require that they be de-rated for active power output, narrowing further the available range of control. The smallest diesel unit at Lerwick is rated at 3.5MW, followed by a number rated at 4.6MW. Two diesel-fuelled gas turbine units are not subject to this constraint, but their use in non-emergency situation is strongly discouraged on cost grounds. Available LPS "spare" capacity to compensate for fluctuations in wind generation output is therefore relatively small, particularly when few LPS units are running in response to low Shetland demand.

2.3 Effects of Shetland Demand Level

As noted above, the level of demand supplied from the Shetland network will determine the number and identity of LPS units which are synchronised to the Shetland distribution system. In turn this will affect the inertia of the system and its response to unplanned generating unit losses or variations of wind generation output. In addition, short-term variations in demand may serve to exacerbate the effects of changing wind output.

2.4 Frequency Constraints

Frequency constraints on the acceptability of additional wind generation will be set by the change in system frequency caused by a sudden loss of wind generation, as a result of a power system disturbance such as a transient fault which does not permanently disconnect load. The effects on generation of a fault on the Shetland network are likely to be more severe than on the mainland network, in terms of both the duration and the depth of voltage depression experienced. As a result, it is questionable as to whether fault ride-through capability specified for wind generators operating under mainland conditions would be effective under all faults experienced on Shetland. Therefore, it is possible that some fault conditions might give rise to the disconnection of all connected wind generation. Since this might represent a serious loss of generation output if a significant volume of wind capacity were installed and operating at high output, the consequences of such an event are studied here.

To determine the restriction on the capacity of unconstrained (i.e. firm connected) wind generation presented by system frequency, studies of the frequency change resulting from the loss of all connected wind generating units were carried out at increasing levels of wind generation penetration. Four main programmes of study were undertaken, considering two load levels – minimum Shetland demand (12MW) and 20% into the range from minimum to maximum (19MW) – with and without SVT. Low demand levels were considered since there will be fewer diesel generators operating at Lerwick under these conditions with correspondingly lower levels of system inertia and susceptibility to frequency excursion in response to variations in wind output.

Additional studies were undertaken to investigate the effects of a reduced requirement for generation at Lerwick as a result of new reactive compensation, and alternative dispatch patterns at Lerwick.

In each case, a set of studies was carried out in which wind generation (including the existing capacity at Burradale) was progressively connected in 1MW blocks up to a total of 10MW. Shetland generation was configured in a manner corresponding to that discussed at a knowledge elicitation session with Shetland personnel [1]. Lerwick diesel generation was dispatched using an LPS Dispatch Simulation Tool developed for this study (see Appendix), with SVT export constrained at 18MW. All of the connected wind generation was then tripped and the minimum point of the resulting drop in system frequency was tabulated and plotted. The results are shown in Figure 2 below. It should be noted that the Wind Capacity value shown includes the existing generation at Burradale.

As can be seen from Figure 2, there is a significant difference in system behaviour between cases with SVT running and without SVT. With SVT running, the level of frequency drop increases broadly linearly with increasing connected wind generation, but does not approach the 2% maximum acceptable drop until well beyond the range of wind capacities studied.

Dispatch-related limits apply to two of the cases shown in Figure 2. [redacted]

[redacted]

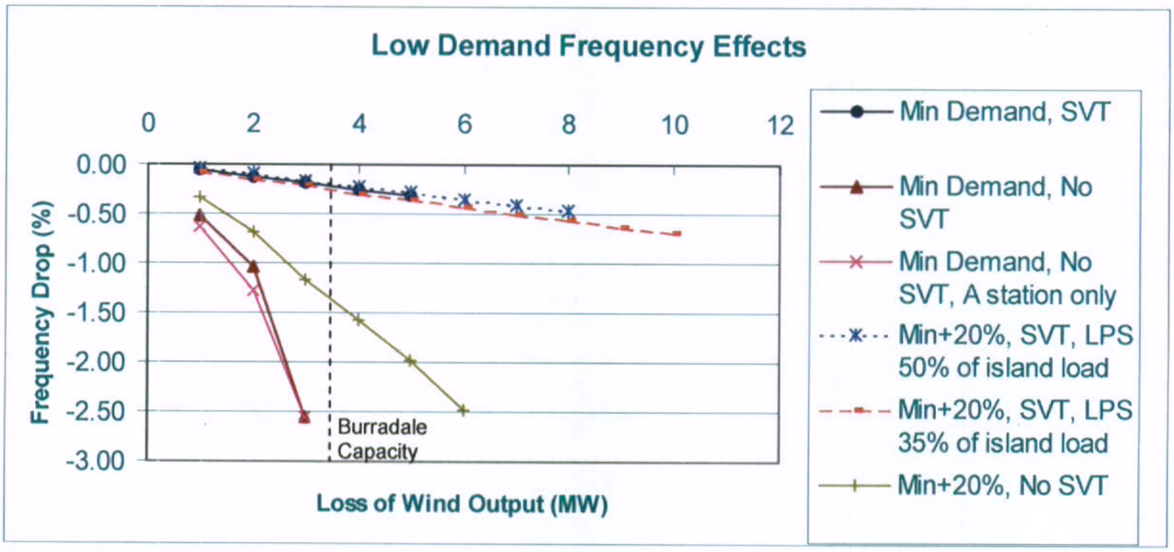


Figure 2: Frequency effects of loss of wind generation at low Shetland demand

It can be seen from Figure 2 that the most extreme case is at minimum demand, without SVT operating. A generator operating under firm connection arrangements would expect to be able to operate under these conditions. Assuming a maximum permissible transient frequency drop of 1Hz or 2%, then it is clear that there is little if any capacity for additional firm connected wind generation beyond the existing development at Burradale with SVT not online. This outcome is explored in more detail in the consideration of de-minimis capacity in the following section.

2.5 De-minimis firm connected wind capacity

2.5.1 Allowable capacity

Small wind generators connected on a de-minimis basis are likely to require connection on a firm basis since no control will be exercised over their routine operations. Integration with an inter-tripping scheme as part of a non-firm connection agreement or with an active management system is unlikely on cost grounds. Furthermore, as minimum cost generation developments, fault ride-through capability is unlikely; it is more likely that such small-scale generators would disconnect in response to a disturbance until acceptable system conditions were restored. Thus in the worst case, all de-minimis generation could be lost in response to a network event causing the maximum credible loss of non-de-minimis wind generation.

To investigate the level of de-minimis generation which could be accepted in addition to the existing firm capacity at Burradale, the total level of wind generation output whose sudden loss would cause a frequency drop of 2% was investigated for the range of total island demand levels from 12MW to 20MW without SVT running. This demand range represents the lowest 20% of demand periods during the year.

Studies were conducted at increments of 100kW of demand. In each case, diesel generation was dispatched using the LPS demand simulator to meet the proportion of demand not supplied from wind generation. Wind generation was added in 100kW blocks until the 2% frequency drop limit was encountered. In each case, the difference between the actual frequency drop and 2% (reflecting the use of 100kW blocks) and the excess frequency drop resulting from the addition of a further 100kW of wind generation were recorded. For selected cases, the consequences of 500kW of excess wind were also studied. The results are presented in Figures 3 and 4.

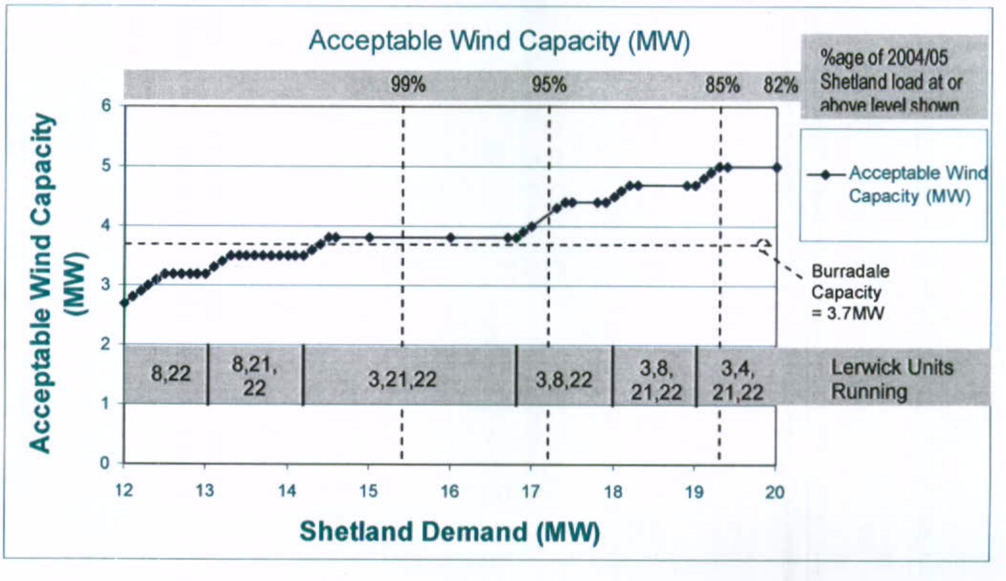


Figure 3: Acceptable level of firm and de-minimis wind generation without SVT running

Figure 3 shows the level of total wind capacity (including Burradale and de-minimis wind, and rounded down to a multiple of 100kW) whose sudden loss would result in a transient frequency drop of 2% (i.e. 1Hz). The graph also shows the LPS running arrangements studied and the minimum load levels experienced for 95% and 99% of 2004/05, and that Shetland demand was below 20MW for 18% of 2004/05. It is notable that the volume of wind which can be accepted onto the Shetland system under these circumstances is dependent only on the generation configuration at Lerwick; there is no discernable effect resulting from the loading on individual generating units at Lerwick. Therefore, the level of acceptable wind capacity shown consists of a series of level portions, during which Shetland demand increases until extra or larger generating units at Lerwick can be started while respecting the 80% unit output constraints on Lerwick units. In the sloped portions of the graph, each additional 100kW of load is met by 100kW of extra wind, until the additional inertia provided by the change in diesel configuration is accounted for. In these sections of the graph, the operating diesel generators will be at a constant output close to 80%.

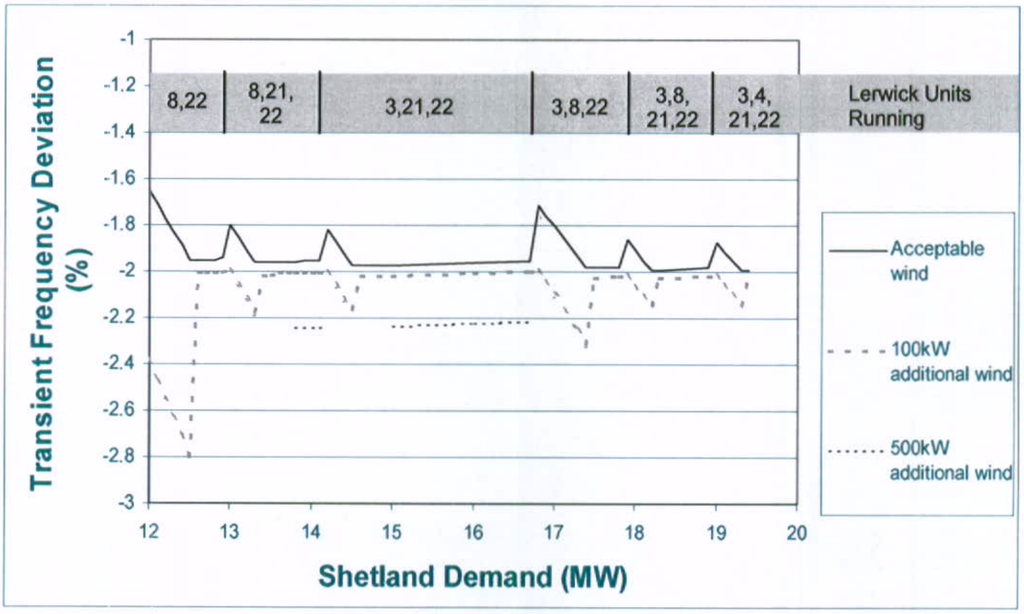


Figure 4: Transient frequency drop for loss of indicated wind capacity and effects of additional wind

Figure 4 shows the transient frequency drop experienced for loss of the acceptable volumes of wind shown in Figure 3, together with the effects of adding a small amount of additional capacity beyond the calculated value. These values are plotted in percent – so that each vertical division represents an additional frequency drop of 0.1Hz. The graph, shows the effect on system inertia of changes to the diesel generation configuration; when the configuration of LPS units is changed, there is an improvement in the minimum frequency reached which is related to the rating of the LPS units started and stopped. As the load grows and more wind capacity is added, the additional inertia of the revised diesel configuration is consumed by the progressively larger wind output at risk of loss.

It can be seen from Figure 4 that the frequency penalty of adding a small amount of additional wind capacity is generally low, except when the change in demand to be satisfied by Lerwick results in a change to the diesel configuration. Provided that the set of operating diesels is not changed, addition of 500kW of wind capacity beyond that strictly acceptable (i.e. adhering to the 2% frequency drop limit) results in an overall frequency drop of about 2.25% or 1.13Hz.

In order for the maximum transient frequency drop of 2% to be breached, there would need to be a network event leading to the sudden loss of Burradale generation together with sympathetic tripping of deminimis wind, coincident with the folloing three conditions:

- There must be an outage of SVT generation.
- Shetland demand must be at a very low level.
- Burradale and de-minimis wind must be generating at a level close to maximum.

Although outages of SVT for maintenance or as a result of unsuitable gas quality are not unknown, this would not be regarded as a common operating condition. [redacted]

Taking these factors into account, a balance must be struck between the volume of de-minimis wind which is to be permitted, and the period for which the network load is low enough that Lerwick generation alone would provide insufficient inertia to avoid a transient frequency drop of more than 1Hz in the event of sudden and complete loss of wind generation. Given the nature of the factors outlined, it would appear reasonable to adopt a the 95th percentile of Shetland load as a suitable standard. From figure 3 above, it can be seen that the next available "step" in capacity would result in a risk of transient frequency frop in excess of 1Hz being incurred for 85% of the year, thus becoming significantly more likely. Therefore, allowing for the existing 3.7MW Burradale development, adoption of a 95% standard permits 500kW of de-minimis capacity to be made available.

It should be noted that this recommendation must be reviewed in the event of change sin the SVT energy supply contract which reduce the availability of SVT generation to SSE, or in the event that SVT generation is closed.

2.5.2 De-minimis Unit Size

In the discussion above it was assumed that de-minimis wind generation would be sufficiently small that the available capacity would be absorbed by a number of small units exhibiting diversity of output. Larger units would inherently present less diversity as a result of their smaller number, and might benefit from greater investment in favourable sites, reducing mutual diversity and diversity in comparison to Burradale.

In its Orkney Registered Power Zone, SSE has adopted the position that only generators falling under the provisions of Engineering Recommentation G83/1 are eligible for consideration as de-minimis capacity. Given the factors outlined above, and for consistency across SSE's Registered Power Zones, it is recommended that this approach should be adopted on Shetland.

Clusters of de-minimis generators may present localised problems on the network. For example if a cluster of generators were to simultaneously attempt to restart following a network disturbance, the local voltage could be adversely effected. To enable SSE to adequately assess any such implications, it is recommended that SSE should be notified in advance - for example in parallel with the planning application for the generator - of prospective new de-minimis connections. This would enable SSE to manage developing concentrations of generators. Low-cost mitigation methods - for example timers to spread the restarting of a cluster of generators over a short period, thus avoiding a single large impact of the local voltage - may be necessary in some circumstances.

2.6 Conclusions

From the foregoing discussion, it is apparent that there is little capacity for additional firm-connected or de-minimis wind generation on Shetland. No additional applications for firmly connected wind generation should be accepted. 500kW of de-minimis capacity might be made available on the basis that the proportion of the year in which a transient frequency drop of more than 1Hz is possible is small, and that even then a set of unusual circumstances would need to arise. Only generators falling under the provisions of Engineering Recommendation G83/1 should be eligible for consideration as de-minimis capacity.

3. System capability for additional wind connected on a non-firm basis

Figure 2 above suggests that with SVT units operating, well in excess of 5MW of new wind generation capacity, in addition to existing Burradale and new de-minimis generation could be accommodated. This would be subject to limits presented by contractual and operational restrictions on dispatching SVT and Lerwick. Previous analysis [3] has suggested that economic factors may lead to additional wind generation in excess of 4MW of new capacity being unattractive to developers. In this section, a fresh energy balance analysis, based on 2004-05 generation and demand data is undertaken.

3.1 Energy Balance Analysis

A number of full-year studies were undertaken to determine the expected energy production of various installed capacities of new wind generation under different combinations of technical and commercial constraints. In each case, measured half-hourly demand and generation data from 2004/05 was used to inform a re-dispatch of generation to calculate the expected output of Lerwick, SVT and new wind generation. Output was calculated for each half hour of the year based on the following set of rules:

- Output of new wind capacity was assumed to be proportional to that of Burradale.
- Minimum Lerwick generation of 40% of island load, as expected following the installation of reactive compensation at Lerwick, was assumed.
- New wind generation will not run unless SVT machines are synchronised and connected to the SSE system.
- When new wind output is available, it will be used to reduce Lerwick output until the 40% minimum is reached. Remaining new wind output will reduce SVT output.
- [redacted]
- SVT output will not be increased at the expense of Lerwick or vice versa.

Half-hourly output was summed to determine the annual energy outputs.

Figure 5 shows the effect of increasing the capacity of new wind development on the output of the four Shetland generation sources.

[Figure deleted]

Figure 5: Annual energy output with increasing new wind capacity.
[Discussion deleted]

Figure 10 shows the output from each of the generation sources with increasing new wind generation

[Section deleted]

From figure 11, it can be seen that wind generation developments beyond 5MW of additional capacity are unlikely to be of economic interest to developers. Opportunities elsewhere in the UK would be likely to yield better load factors and thus more revenue.

4. Operational impacts of additional wind generation

In order to assess the operational effects of additional wind generation on the operation of LPS and SVT, a series of dispatch simulations were conducted using Shetland demand and Burradale output data captured by SSE at a 2-minute sampling interval. Studies were undertaken for installed new wind generation capacities of 0MW to 5MW (based on the Energy Balance limitation identified above) having the same temporal output pattern as Burradale, and for the months of April 2005, August 2005, October 2005 and January 2006.

4.1 Simulation Approach

Based on the knowledge elicitation session with Shetland personnel and subsequent discussions, and on previous analysis work by Strathclyde [], the following simplified dispatch procedure was used:

- B-station units at Lerwick are dispatched weekly, so that at the point of minimum demand over the week, net of wind generation, as close to 40% of Shetland demand as possible is met by B-station units running at between 80% and 100% of rated output, subject to a minimum of two Lerwick diesel units being dispatched. B-station units are not started or stopped during a week.
- A single daily nomination of SVT output is made. This nomination is set at 20% above the minimum required output from SVT during the day after allowing for wind output and LPS at 40% of Shetland demand.
- B-station and SVT nominations are made using perfect knowledge of demand and wind output levels over the relevant period.
- New wind capacity is allowed to run unconstrained, so that its output is scaled from the actual Burradale output in proportion to the new installed wind capacity studied.
- At the beginning of the simulation, SVT is set to its nominated output level. A-station units are started (and the output of running B-station units is adjusted) to balance Shetland demand net of Burradale, new wind and SVT output. All LPS diesel units operate at the same percentage of rated output.
- At each two-minute simulation step, SVT output is adjusted to balance demand, wind output and LPS output. This leads to a mismatch between the nominated SVT output and the simulated value.
- A "balancing" redispatch of LPS is made to return SVT to its nominated output. If SVT is producing more than the nominated level, LPS output must be increased; if SVT is producing less than the nominated level, LPS output is decreased. A-station units are stopped and started as necessary to maintain output between 80% and 100% of rating, but no fewer than two LPS units can be run. Where these two conditions cannot be simultaneously fulfilled, two units are run at 80% and imbalance of SVT output in comparison to nomination remains. As before, the output level of B-station units is adjusted, but no B-station units are started or stopped.
- In line with assumptions made in a previous Strathclyde study of Shetland, the implementation of the balancing dispatch at LPS is delayed for 5 sample steps, or 10 minutes. No knowledge of future demand or wind output levels is used in the balancing redispatch. Thus variations in wind or demand are met entirely by SVT in the short-term, with LPS being adjusted to return SVT to its planned position thereafter.

4.2 Comparison of Actual and Simulated Dispatch

[Sections deleted]

Comparison of Figure 11 with Figure 12 and Figure 15 with Figure 16 shows that the simplifying assumptions made in the modelling result in a greater short-term balancing duty on SVT as a result of not taking account of predicted load changes when dispatching Lerwick units, and increased longer-term balancing duty on Lerwick A units as a result of returning SVT rapidly to its planned output. These factors result in greater use of Lerwick A units with the simulation resulting in greater energy production by A station units together with an increase in their operating hours and starts and stops in the simulation over the actual dispatch.

Notwithstanding these differences, the simulations conducted with no new wind capacity allow the establishment of a set of "base case" results, which can be compared with simulations modelling additional wind capacity to quantify the additional balancing duty which would be imposed on Lerwick and SVT by the connection of new wind generation. Such comparisons are discussed in the following sections.

4.3 Effects of New Wind Generation

4.3.1 Lerwick Operating Hours

[Sections deleted]

From the graph, it can be seen that there is a general increase in the amount of energy delivered by A station units as additional wind generation capacity is connected. As before, the effects of large wind volumes displacing A station operation in October can be seen. The increase in electricity production is as a result of increased unit operation to balance shortfalls in wind generation output. As will be seen below, the increase is at the expense of SVT, whose output is reduced. The magnitude of increase ranges from 200-300MWh per month for each 1MW of new wind capacity connected. Taken as a percentage of output with no new wind, this corresponds to an increase of approximately 3-6% for each additional 1MW of wind capacity.

4.3.2 Lerwick Unit Starts

Figure 21 shows the variation in the number of times that an A station unit at Lerwick is started over the month.

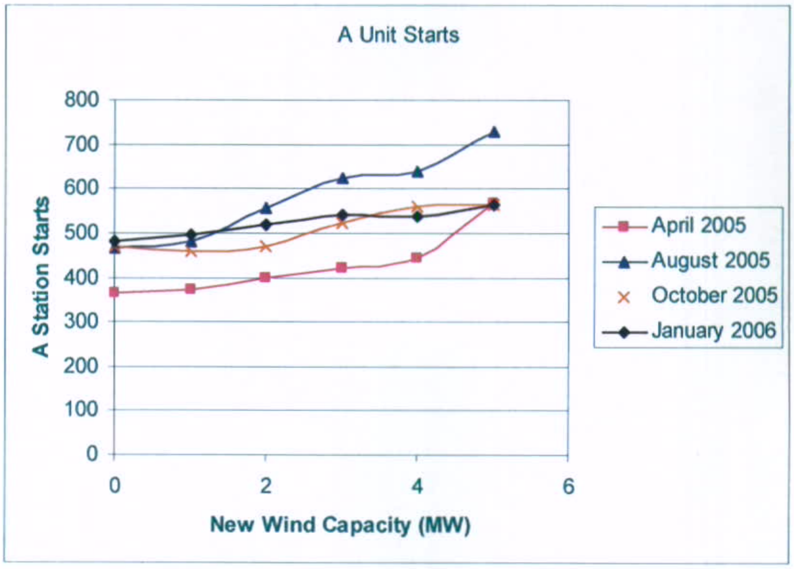


Figure 21: Effects of additional wind on Lerwick A station generator starts

The effects shown in Figure 21 are notably less linear than in the operating hour and energy production graphs, a result of a changing balance between long and short-duration operation of units. Comparing Figures 19 and 21, when the number of starts increases more steeply than the operating hours, a greater proportion of short-duration operation is taking place. Therefore, this effect becomes more pronounced with higher installed capacities of new wind. While this duty might be supported by permitting SVT to assume a more volatile output profile, and run further from its nominated output for longer, the risk of objection by SVT to an increased balancing role must be taken into account.

The variation in the profiles of the curves in Figure 21 results from the combined effects of the variability in demand and wind output, and the level of available adjustment in the output level at Lerwick without starting and stopping units – this is proportional to the broad level of output from Lerwick, since more units will be operating and available to scale their output between the minimum and maximum permissible levels.

From Figure 21, it can be seen that there is a general rise in the number of stops and starts of Lerwick units as more wind is connected. The effect is not linear, so that addition of 1MW of new wind will produce different effects depending on the time of year and the existing wind capacity. However, the increase appear to be more pronounced when Shetland demand is low than in months of high demand.

4.3.3 SVT Energy Output

Figure 22 shows the effect of increased wind generation capacity on energy production by SVT.

[Graph deleted since shows historic SVT output levels]
Figure 22: Effects of additional wind on SVT output

As can be seen, energy production by SVT is reduced by approximately 800MWh per month for each additional 1MW of wind generation connected. This rate of reduction is more pronounced than that indicated by the energy balance calaculations above as a result of increased energy output from Lerwick in balancing variations in wind output. In each month, the nominated and simulated energy production totals are within 100kWh of one another.

4.3.4 SVT Balancing Duty

To evaluate the additional duty placed on SVT in balancing variations in wind capacity, the average level of unbalance between the nominated and actual SVT output levels was calculated for each half hour of each month. These values wre tabulated in 0.25MW divisions to produce the frequency distributions shown in Figures 23 to 26

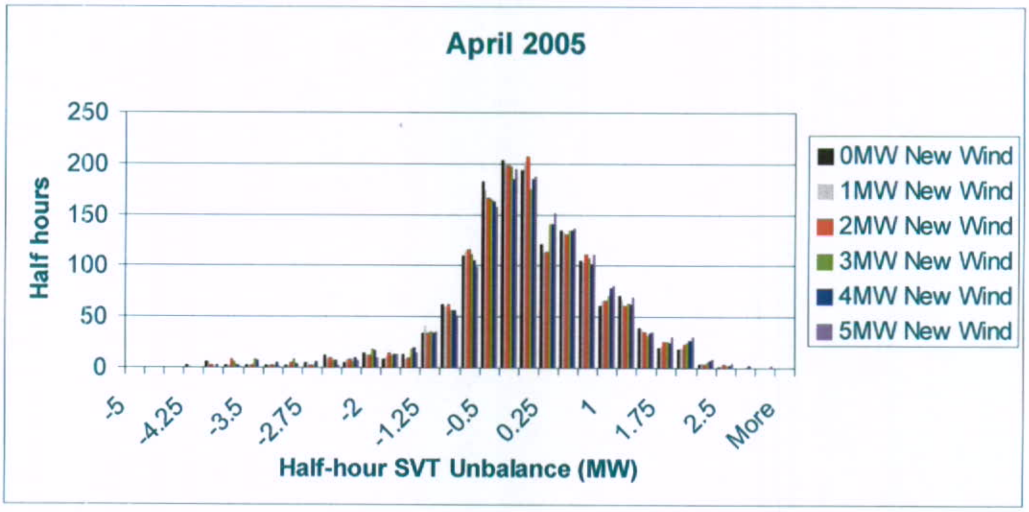


Figure 23: SVT half-hourly unbalance distribution in April 2005

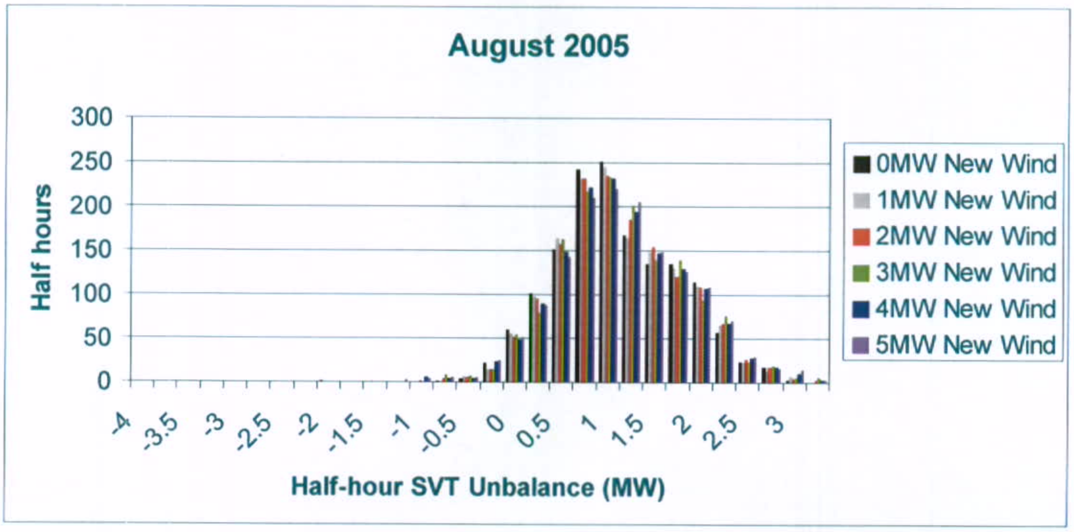


Figure 24: SVT half-hourly unbalance distribution in August 2005

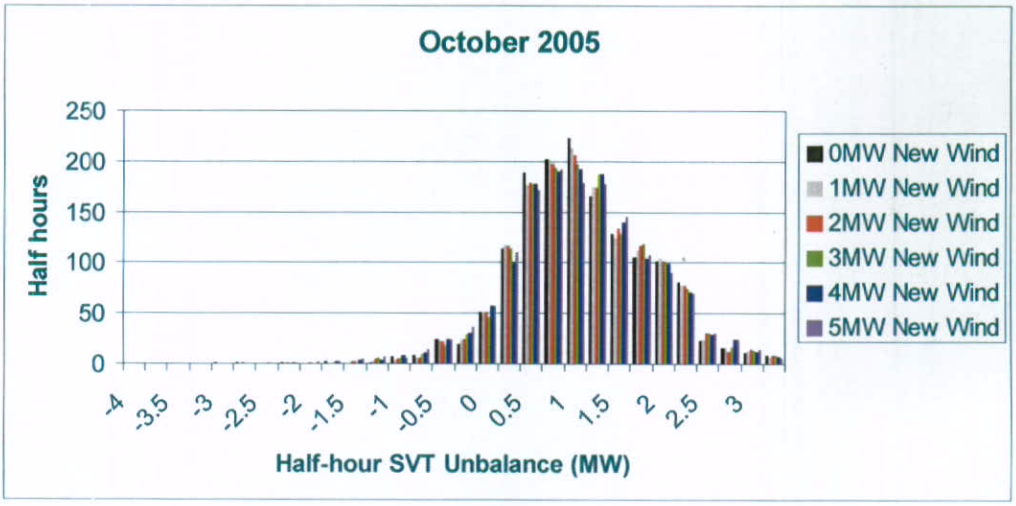


Figure 25: SVT half-hourly unbalance distribution in October 2005

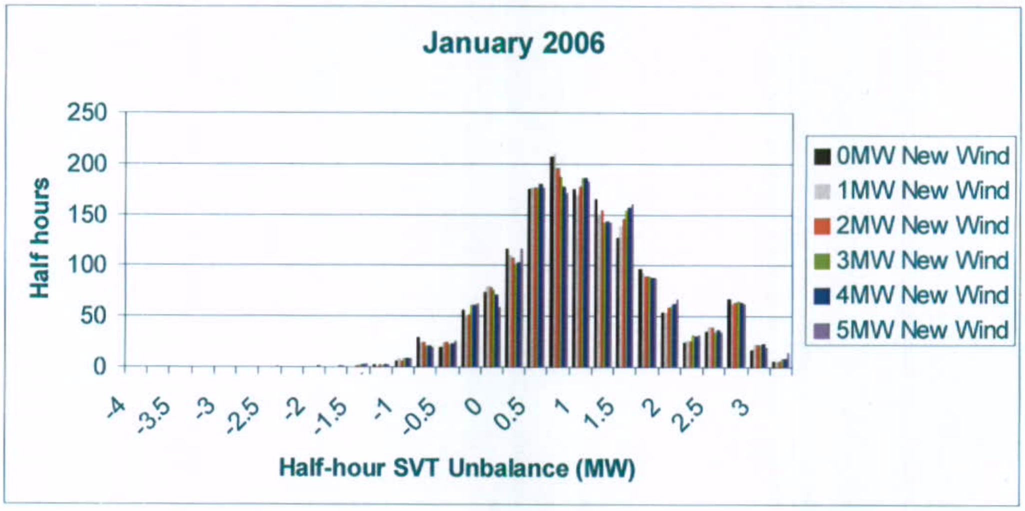


Figure 26: SVT half-hourly unbalance distribution in January 2006

As discussed above, the simulated dispatch aggressively adjusts LPS output to return SVT to its planned output level 10 minutes following a change in demand or wind output. Therefore, the values shown in figures 23 to 26 are likely to be attributable to sudden large changes in demand or wind output together with a contribution from continuous volatility of wind output over half-hour periods.

From the graphs it can be seen that variations in demand and Burradale output are the most significant influences on SVT's balancing duty. The general effect of additional wind generation is to modestly increase the number of half hours in which SVT is generating significantly more than nominated and to reduce the number of half hours in which SVT generates less than nominated or slightly more than nominated. It is, however difficult to describe a specific relationship between the volume of additional wind and the pattern of unbalance between nomination and output.

In practice, the Shetland operators' understanding of the demand profile allows the effect of demand variationto be mitigated by pre-emptive dispatch of Lerwick generation to reduce the short-term impact of large load steps associated with time-switching of load, so that the actual overall level of large short-term unbalances between SVT nominations and output is reduced. This effect is however offset by an increased tolerance of smaller, longer-term unbalances in which SVT output is allowed to vary with the general shape of the daily demand profile.

4.3.5 Conclusions

From the foregoing analysis, it is clear that that addition of new wind generation capacity on Shetland will impose an increased requirement for short-term balancing activity on LPS and SVT. For the dispatch process adopted here, most of this extra duty falls on A station units at Lerwick, resulting in increases in operating hours, energy output and unit starts and stops, while increases in variability of output on SVT are more minor. SVT energy production is reduced to a greater extent than in the half-hourly energy balance studies discussed in the previous section. However, an operating approach requiring less aggressive restoration of SVT output to the planned position would be expected to divide the balancing duty more towards SVT.

The increase in energy production by A station units at LPS brought about by their increased balancing activities comes at the expense SVT output. SVT output is therefore reduced more rapidly in these simulations than was indicated by the energy balance study discussed earlier. [redacted]

5. Economic effects of additional firm and non-firm connected wind generation

5.1 Energy Purchase Costs

From the energy balance and operational analyses described above, it appears that a realistic operational strategy (in which LPS and SVT are controlled to share the balancing duty arising from demand variation and wind output variability) might result in the output of new wind capacity offsetting SVT generation only, with the level of output from LPS being largely unchanged. To gauge the sensitivity of the economic result to this effect, three cases are considered:

- The energy balance result, in which both SVT and LPS output reduce
- The operational simulation result, in which LPS output increases at the expense of SVT. A rate of increase of 3% per MW of new wind is assumed.
- A median case in whch SVT output reduces, but LPS output is constant.

In the analysis, the level of output from new wind generation output given by Figure 10 (i.e. only modestly constrained up to 5MW of capacity) was assumed, with SVT output being reduced when additional LPS output was required.

The following energy purchase costs are considered in this analysis:

[Deleted]

Two wind energy costs are considered as it is expected that the level of support provided by ROCs will decline as wind generation technology develops and becomes more economically competitive with other generation types.

[Deletions]

5.2 Effects of Deminimis Capacity

From the perspective of the operational dispatch simlation discussed in section 4, the inclusion of 500kW of de-minimis generation might be expected to have a similar effect to 500kW of new large wind generation, in that the demand to be satified by LPS and SVT is reduced. Increased diversity of such small capacity over a single 500kW development might however be expected to result in reduced variability of total output and this a lower balancing duty on SVT and LPS. Indeed, it may be that 500kW of de-minimis capacity could be balanced by SVT alone with incurring extra operational duty on LPS.

Since the effect of de-minimis generation is to reduce the overall volume of energy that must be purchased, its cost is effectively that of energy sales foregone as a result of customer generation. At 9p/kWh, this corresponds to a generation cost of £90/MWh. Given that the cost penalty of reduced SVT generation is still likely to be incurred, the addition of de-minimis generation is slightly less economically favourable than new large wind capacity.

6. Prospective mitigation solutions

From the economic analysis, it is clear that under the present contractual arrangements the benefits of additional wind generation connections are maximised when the output from this generation displaces LPS output to the maximum extent, and SVT output is changed as little as possible. This would involve reducing the amount of additional energy produced by LPS as a result of balancing variations in wind output, and maximising the daily energy production of SVT to offset the remaining balancing duty on LPS. A number of possible approaches to this problem might be considered:

- Requiring wind generators to provide frequency response capability – for example by holding a percentage of capacity in reserve at full output, which is then used either to increase output when the wind drops slightly, or to compensate for reduced output by other wind generators. This would require wind generators to forego capture of some available wind energy, reducing their annual load factor. It is unlikely that this measure would balance more than small variations in wind output without the reduction in load factor making the development economically unattractive to investors; variations resulting from high-wind-speed cutout of generators could probably not be balanced to any significant extent by this method.

- Requiring wind generators to stagger high-wind-speed cutouts and machine starts across their turbines, or between developments might reduce the incidence of sudden large increases or reductions in wind energy production. However, careful analysis of wind diversity at and between development sites would be required to ensure that startup and shutdown points were not selected in such a way as to create coincident starts and stops which would not otherwise have occurred. Ultimately, real-time communication based coordination of sites might be required.

- Better prediction of wind energy availabilty would permit LPS and SVT generation to be pre-emptively controlled to follow broad patterns of wind generation output. The utility of such a method would however be restricted by the current practice of making a single daily nomination of SVT output and the long lead time between nomination and delivery. The main benefit of this measure taken alone would probably be in better planning of LPS units starting and stopping to follow the wind and demand profile.

- Nomination of individual half-hourly energy production by SVT (as permitted by the contract), rather than single values for each day would permit SVT to more closely follow the load profile, thus reducing the extent to which additional LPS units must run to follow the daily demand profile. Reducing the period for which nominations must be submitted at once (for example from 24 hours to 6 hours) and the time ahead of delivery at which the nominations are made would permit SVT to better follow forecasts or available wind energy, again maximising its utilisation. However, increased output from SVT to balance unexpected short term variations in wind output or demand might risk violation of the protection-imposed export limit on SVT at times of high nominated output; as a result constraints on the maximum nomination level related to the volume and volatility of connected wind generation might be necessary.

- Improved controls on LPS diesels would allow LPS to play an increased role in short term balancing of wind and demand variations. This would tend to reduce the short-term departures of SVT from the nominated output levels, permitting levels of nomination closer to the protection-imposed limit without risk of tripping.

- Installation of energy storage would reduce the balancing duty on both LPS and SVT, reducing the additional unit operation and energy production by LPS for balancing purposes, and permitting balancing to be undertaken using cheaper stored wind energy rather than LPS or SVT production, although this latter point would be subject to the cost of wind energy and the efficiency of the storage technology. Furthermore the provision of voltage support by the energy storage system would permit the minimum output of LPS to be reduced beyond the current 40% of Shetland demand, thereby facilitating either SVT operation at a more economically favourable point on its unit energy purchase price characteristic, or an increase in wind generation output.

7. Conclusions and Recommendations

- No more firmly-connected large wind generation can be accepted onto the Shetland network.

- Up to 500kW of de-minimis wind generation might be accepted on the basis that the period during which problems might arise is low

- Between 4.5MW and 5MW of additional wind generation could be connected without experiencing significant constraint on its output [redacted]. The mechanism for achieving this in operational timescales is not clear since the capability is not great for active dispatch and re-dispatch of generating units on the Shetland system.

- Short-term variations of wind output will increase the requirement for LPS and SVT to vary their output to balance variations in demand and wind generation. The ability of SVT to participate in this balancing will be dependent on contractual restrictions and the willingness of SVT to permit plant output to deviate from the nominated level beyond the short term.

- Restrictions on the ability of SVT to participate in balancing wind variations will place additional demands on Lerwick. Lerwick output may rise as a result of energy produced to balance shortfalls in wind energy output.

- Trade-off likely in the operational impact of additional wind on LPS operations. Running hours will increase if additional balancing duty is required (since voltage-related minimum must not be breached) as will the number of starts [redacted] 80% minimum loading violations will likely increase if the number of starts and stops is to be restricted.

- [redacted] At current cost levels additional wind generation capacity is at best marginally viable, and at worst significantly more costly than the current generation portfolio.
- *Assessment of most promising mitigation solutions.*

8. References

[1] "Transcript of Knowledge Elicitation on Shetland Generation Operation", Document SSE/SHET/KT/2006-001, February 2005.

[2] "Notes on Lerwick Power Station Dispatch Simulation Tool", Document SSE/SHET/TR/2006-001, March 2005.

[3] "Estimation of Viable Shetland Isles Wind Generation Capacity"

Appendix: Notes on Lerwick Power Station Dispatch Simulation Tool

1. Introduction

The LPS Dispatch Simulator Tool is a collection of Visual Basic code for Microsoft Excel whose purpose is to simulate the dispatch of diesel generators at Lerwick Power Station. The tool implements the principles discussed at a knowledge elicitation session with Jeremy Duncan and Bob Kelman of SSE [1]. This document describes the installation and operation of the tool.

2. Installation

The tool can be operated by manually opening the spreadsheet file containing the code – LPSdispatch.xls – and running the "Dispatch" macro. However if the tool is to see more than occasional use, it will be more convenient to install a toolbar button to run the tool. This can be accomplished using the following steps:

1. Ensure that the file containing the code – LPSdispatch.xls – is stored in a suitable permanent location on the local machine or a file server
2. Open the file in Microsoft Excel. When prompted, enable macros.
3. Open the "Customise" dialog in Excel – from the Tools menu, select customise
4. On the Toolbars tab, press New to create a new toolbar. Give it a suitable name. A new toolbar will appear, floating over the open document.
5. Select the Commands tab, and from the left pane, select Macros
6. Click and drag either "Custom Menu Item" (for a button with text) or "Custom Button" (for a button with a picture) onto the newly created toolbar.
7. Optionally, change the text or picture on the new button by right-clicking it and selecting "Name", "Change Button Image" or "Edit Button Image"
8. Right click the newly created button and select "Assign Macro"
9. From the list shown, select "Dispatch" and click OK
10. Close the "Customise" dialog
11. The dispatch tool can now be started by clicking the new button. If desired, the new toolbar can be "parked" at the top of the screen with the existing toolbars by clicking and dragging its name.

3. Operation

When the tool is started, the dialog box shown in figure 1 will appear. This box provides all input and output facilities. It is divided into three main areas:

- The Shetland Conditions area enables the setting of general background conditions which determine the output required from LPS.
- The LPS area enables the selection of "B station" units, which are generally dispatched to operate for a week or more at a time, and shows the dispatched output of all LPS diesel-engined units.
- The Dispatch Mode area enables the selection of the dispatch method to be applied, and starts the dispatch process.

Each of these areas is described in more detail in the following sections.

3.1 *Shetland Conditions*

This area permits the setting of general background generation and demand conditions which determine the level of output required from LPS. Values in this area are continuously updated as other values are changed. Four main settings are available:

- **Shetland demand and total wind generation output:** These items are "absolute" settings - they affect other values in the "Shetland Conditions" area, but are not changed as other values change.
- **SVT output:** SVT can be switched on or off, but its value is calculated to be that portion of the load not supplied from other sources. Optionally SVT output can be restricted to winter or summer line ratings.
- **LPS output:** LPS output can be adjusted as a percentage of total Shetland demand; this corresponds to current operational practice, in which the lower limit on LPS generation to avoid voltage instability is expressed in this way. MW output is also shown for information. LPS output can only be edited when SVT runs; at other times it is fixed by demand and wind output. When SVT output is restricted by line ratings, LPS output has a minimum constraint – the value shown must be at least the remaining demand to be supported when SVT is at the selected limit. It is recommended that restrictions on SVT should be lifted while LPS output is adjusted and then reimposed; this will avoid difficulties in entering new LPS output values.

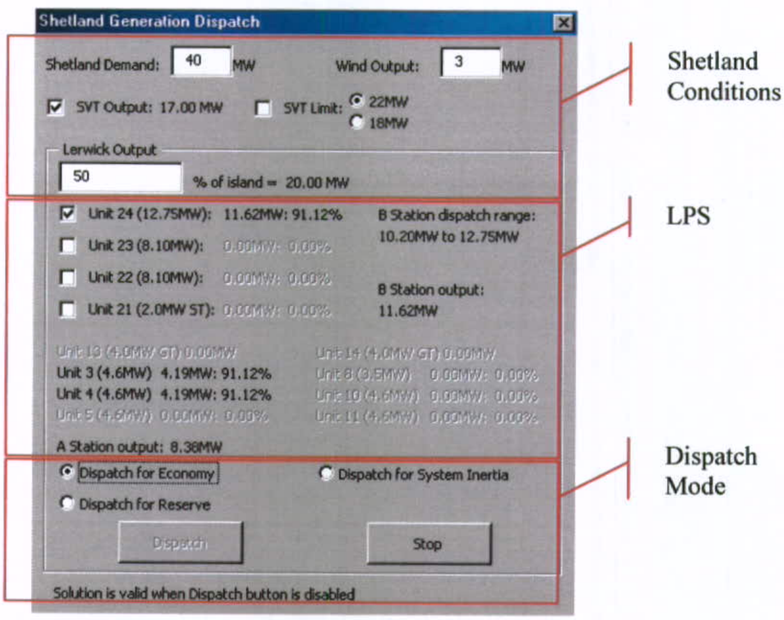


Figure 1: LPS Dispatch Simulation Tool

3.2 *LPS*

The LPS section shows the dispatched power outputs and percentages on rating of each diesel and steam turbine unit at LPS. Values shown here are only valid immediately following dispatch; they will be invalidated by any change to the Shetland Conditions section or to the selection of B station units. For convenience, the "Dispatch" button is disabled when the figures are valid.

3.2.1 B Station

The four B station units are listed at the top of the LPS area. These should be switched on and off manually using the check boxes. Unit 21 is only available when at least one other B station unit is running; its output is assumed to be proportional to the *total* B station output – i.e. the full 2MW rating is only available when units 22, 23 and 24 run at full output. For convenience in selecting an appropriate combination of units, the possible output range (i.e. from 80% to 100% of rating on selected diesel units, plus proportional unit 21 output) is shown.

3.2.2 A Station

A station units are dispatched as required to supply LPS output not supported by B station units. For each unit, the dispatched power output and percentage on rating is shown.

3.2.3 Units 13 and 14

Units 13 and 14 are not dispatched by this tool. They are diesel-fuelled gas turbine units and are only used in particular circumstances, such as a serious shortage of spinning reserve. If use of unit 13 or 14 is required, its effect on the LPS dispatch can be simulated by reducing the LPS output percentage figure to reduce the displayed LPS MW output by the total output of units 13 and 14. If SVT is not running, this can be achieved by making a corresponding increase in wind output.

3.3 Dispatch Mode

The dispatch mode area offers three different methods of dispatching LPS generation. These methods differ in the output level at which the required number of LPS units is calculated, and the order in which A station units are dispatched. In some circumstances, this results in a different number of operating A station units. At low LPS output levels, where the demand cannot be matched while satisfying the normal 80-100% output range, the different methods will produce differing results.

- **Dispatch for Economy:** In this mode, the number of units required at 100% output is calculated; units are then reduced in output to match the required figure. A station units are dispatched in order from largest to smallest. This method results in the smallest possible number of running units. Where the 80-100% constraint cannot be met, this method will run a smaller number of units in excess of 100% output.
- **Dispatch for Inertia:** In this mode, the number of units required at 80% output is calculated; output is then increased to match the required figure. A station units are dispatched in order from smallest to largest. This approach results in the largest possible number of running units. Where the 80-100% constraint cannot be met, this method will dispatch an extra unit and run all at less than 80% output.
- **Dispatch for Reserve:** In this mode, the number of units required at 80% output is calculated; output is then increased to match the required figure. A station units are dispatched in order from largest to smallest. Where this approach dispatches the same

number of units as “Dispatch for Inertia”, the units may be more lightly loaded, providing greater spinning reserve. Where the 80-100% constraint cannot be met, this method will dispatch an extra unit and run all at less than 80% output.

It may be advantageous to examine the results of all three dispatch methods to determine the best dispatch pattern. In most cases, the results will not differ. At low LPS output levels, some methods may be able to meet the required LPS output while respecting unit output constraints while others may not.

The Dispatch button calculates the required output levels from each generator to meet the specified LPS output. All operating generators with the exception of unit 21 are dispatched to the same percentage of rated capacity. As described above, unit 21 output depends on the operation of B station units. When the Dispatch button is available for use, all results shown should be regarded as invalid.

The Stop button stops the LPS dispatch simulation tool.

4. References

[1] “Transcript of Knowledge Elicitation on Shetland Generation Operation”, Document SSE/SHET/KT/2006-001, February 2005.