

The Integration of Renewable Energy into the Electrical Distribution Network on Achill Island, Ireland

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Abstract: This paper examines the degree to which renewable energy sources can be integrated into the existing electrical distribution network on Achill Island, Co. Mayo, Republic of Ireland, and the changes required of the network to maximise their penetration. It forms part of a wider European Altener contract no. AL/4.1030/C/00-0013, a study to formulate local plans for a number of European islands aiming at 100% renewable energy supply (RES), to identify issues related to the large scale deployment of RES. This overall study for Achill Island has been driven by the Mayo Energy Agency who promote energy efficiency, conservation and renewable energy in the region. Islands present many advantages for this kind of study as they usually possess a significant RES potential, whilst being highly dependent on energy imports. They often experience large seasonal variations in energy demand due to tourism and are sensitive to the adverse environmental impacts associated with the use of conventional fuels.

Keywords: Achill Island, Renewable Energy, Wind Energy, Tidal Flow, Loadflow Analysis.

1. INTRODUCTION

The primary objective of this paper is to examine the amount of distributed electrical generation from RES that can be fed into the electrical distribution grid on Achill Island. This is presented from the point of view of current energy demand and electrical network conditions and also offers a prediction in respect of future demand coupled with a planned upgrade of the network from one 10kV feeder to two 20kV feeders. This upgrade is part of a national plan to convert all 10kV networks to 20kV in order to increase capacity and bring about a reduction in transmission losses [1].

The analysis of connected generation is carried out using SynerGEE Electric 3.0, a

commercially available load flow analysis software package commonly used by electricity utilities [2]. The network information for Achill Island was supplied by ESB (Electricity Supply Board, the national electricity utility in the Republic of Ireland). The energy demand for the island has been determined through an energy audit carried out by the Mayo Energy Agency as part of the Altener contract [3].

In a wider context it is planned that ultimately all energy used on the island, currently supplied either directly by a mixture of fossil fuels or through electricity delivered via the national grid, be entirely replaced by energy from renewables sourced from the island and/or surrounding marine area. This is an unlikely scenario in the short to medium term. One of the barriers to this is the direct replacement of all transportation fuels from locally produced energy sources. As a compromise to this aim the RES available should be able to indirectly replace current and future energy consumption on a kWh/TOE (tonnes of oil equivalent) basis.

1.1 Achill Island and RES

Achill Island is the largest island off the coast of Ireland, with an area of 132 sq km and is linked to the mainland by a short bridge. It has a population of approximately 2800 distributed within seven main villages and a number of smaller clusters of homes. Renewable energy resources considered in this study are wind and tidal flow.

1.2 Electrical Distribution Network

The electricity supply to the island is via an underwater cable from the mainland, running along side the bridge. This constitutes a single distribution feeder that serves the whole island, largely three phase, but including a significant proportion of single phase distribution to the more remote areas. There are many such networks within rural Ireland and most are remote from generation plant and serve

sparingly distributed loads, leading to ‘weak’ grids where fault levels are low [4]. This feeder is one of two which originate from the 38kV/10kV substation located on the mainland at Polranny, approximately 2km from the bridge. This feeder supplies power through transformers at the local voltage level to residential, industrial, commercial and public service customers. ESB provide figures of 2.31MW and 2.36MW (winter and summer) maximum loads at the substation (serving the two feeders), with approximately 28% of these loads originating from the Achill and Currane feeder shown in Fig. 1.

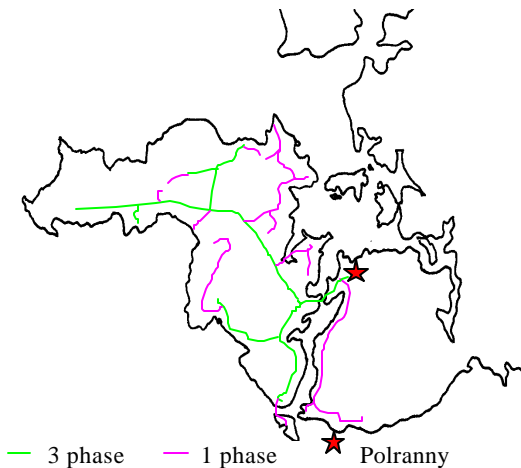


Figure 1. Achill Island 10kV Feeder

2. METHODOLOGY

To assess the amount of distributed generation that may be connected to the network, a computerised method of network analysis was used, contained within SynerGEE. This enables power flows, voltages and fault levels to be determined throughout the system. The electrical network data was made available through ESB, who use SynerGEE to carry out operational studies on a day-to-day basis.

2.1 Current Demand and Infrastructure

Preparing the network to assess generators

Once the databases are imported, the task of allocating loads throughout the network was carried out, according to the apparent power kVA rating of transformers local to customer demand. This total distributed load is based on figures provided by ESB for the demand at the point of the 38kV supply to the substation at Polranny, split in the proportion of each feeder demand as specified in the database.

In order to assess the impact of distributed generators, ESB sets out a worst-case scenario for their effects with a network starting condition (before additional generation is connected) of 20% of the maximum known load for the feeder in question. This is considered to be the minimum load on most networks in practice and historically has been found to give accurate predictions in feasibility studies of this type.

The Load Allocation function within SynerGEE provides values of active and reactive power flows, currents and voltage drops from the nominal feeder source voltage on all sections of the network. The Fault Analysis function informs of resistance (R) and reactance (X) from each section back to the infinite bus (400kV level), and can therefore calculate balanced line to line and three phase fault levels throughout.

Connection of generators – wind turbines

From examination of the local wind resource, the layout and characteristics of the electrical network and the restrictions on the island due to the presence of National Heritage Areas (NHAs), Special Areas of Conservation (SACs) and town perimeters, an assessment was made of the likely position of wind turbines [4]. A network connection point was identified in close proximity, and an estimation of generation capacity treated as negative load was connected to the chosen section within SynerGEE. Through load flow analysis the voltage rise at that section (point of common coupling, pcc) was identified and compared with the voltage level prior to connection of the generator. This voltage rise is one of the limits placed on the amount of generation which may be connected. These limits are determined by ESB and are set out in Table 1.

Table 1. Limits On Connected Generation

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|--|
| <ol style="list-style-type: none"> 1. 1% voltage rise at minimum load. 2. < 10% voltage drop on loss of generation. 3. Maximum 3% line losses between generator and pcc. |
|--|

Item 2 in Table 1 can be verified by ensuring that the connected kVA of the generator is less than 10% of the lowest fault level at the pcc prior to connection of the generator. The assumption is made that any connected generator in this study will be an induction type and will therefore provide little or no contribution to the fault level originating from the infinite bus.

2.2 Future Demand And Infrastructure

As the planned upgrade of the network from one 10kV feeder to two 20kV feeders is likely to commence in 2003, a short term future prediction of energy demand involves the assumption of a small increase, coupled with the availability of the upgraded network and the associated connection of an increased amount of wind powered generation. In the medium to longer term it may be economically feasible to also consider the tidal energy potential identified at Bullsmouth. ESB provide a figure of 4% increase in demand per year until 2010. Through consultation with ESB it was decided to model the network upgrade by splitting the existing feeder into two (roughly in proportion to current demand), converting the main feeder to Bullsmouth from single to three phase and analysing this using SynerGEE at the new voltage level. This is shown in Fig. 2.

Connection of generators – wind and tidal flow turbines

A similar process to that described in section 2.1 was carried out, using the demand increase predictions from ESB. The availability of a three phase supply local to Bullsmouth allows a connection to be made to tidal flow turbines.

Geothermal Energy

This was considered as a possible efficient solution to the current high consumption of fossil fuel energy for space heating and hot water requirements within domestic properties, with the additional electrical load for the geothermal heat pump systems being supplied from renewable energy generators on the island.

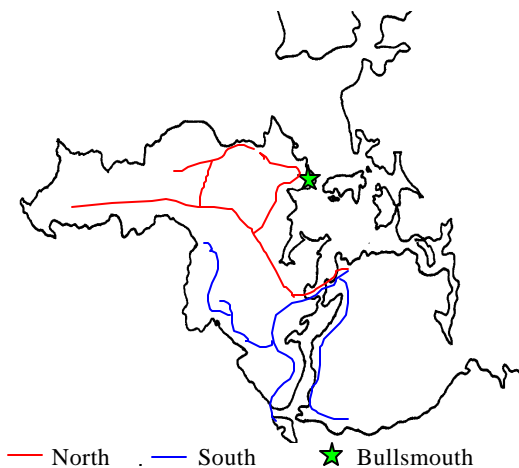


Figure 2. Proposed 2 x 20kV Feeders

2.3 Determination Of Energy Produced From Renewable Energy Sources

Wind turbines

From the wind data and a performance curve for a typical wind turbine of a size determined according to Table 1, an annual energy calculation was performed. RETScreen was used for this and the details can be found in Appendix 1 [5]. RETScreen calculates a probability distribution from the wind data and applies this to the wind turbine power curve to give a predicted energy yield. This energy yield figure can be compared directly with the energy consumption figures contained in the energy audit, so as to determine how much of the current and future annual energy demand has been displaced.

Tidal flow turbines

In the case of connection of a tidal flow turbine array at Bullsmouth, a study was carried out by University College Galway (UGC) as part of the Altener contract [6]. This provides figures for predicted energy yield and generation capacity for a proposed array of tidal flow turbines. Dependent upon how much of this generating capacity can be connected to the network with regard to Table 1, the portion of future energy demand displaced can be determined.

3. RESULTS

The results are presented in three sections. The first section deals with the current electrical network and energy demand situation. The second section examines future demand coupled with the up graded network allowing additional amounts of generation to be connected. Finally comparisons are made between generation and the percentage of energy displaced.



Figure 3. The network as shown in SynerGEE

3.1 Current Demand and Infrastructure

Table 2. Information from ESB

Substation capacity:	5MVA
Substation secondary nominal voltage:	10.8kV
Maximum loads for Polranny substation:	
Winter:	12.30 1.52MW
Winter:	18.00 2.31MW
Summer:	2.36MW
Portion of loads from Achill feeder:	28%
Power factor (pf) at substation:	95%
Load type:	40% current, 60% impedance

The minimum load is 20% of 28% (Achill) of the lowest maximum load shown in table 2.
Distributed load from feeder: 88.9 kVA

Table 3. Loadflow and Fault Analysis

All regulators on network set to neutral taps		
Section 4275297 (chosen as pcc)		
Distance from substation: 7.8 km		
Load into section: 5kW 1kVAR 0A		
Voltage at pcc: 99.8% x 10.8kV		
Fault Analysis:		
	R (ohms)	X (ohms)
Substation	1.25	2.99
4275297 (pcc)	7.59	5.97
Fault Levels:		
	line - line (MVA)	3 phase (MVA)
Substation	17.9	20.7
4275297 (pcc)	5.9	6.9

A chosen location for wind turbines is shown in Fig. 4.

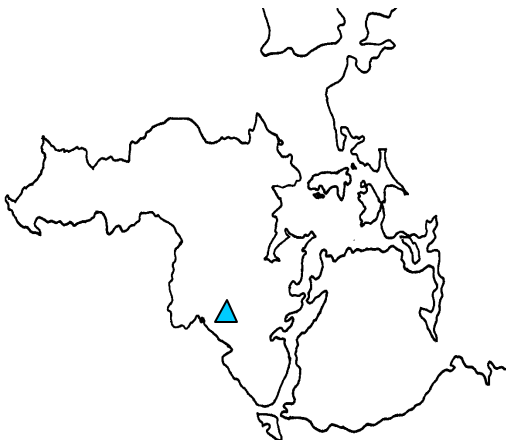


Figure 4. Location of Wind Turbines

Connection of Generation – Wind Turbines

Fig. 5 is an extract from SynerGEE showing a portion of the existing network and the new section of line from the generator to the pcc.



Figure 5. Generator connection in SynerGEE

The results of connecting **200kW** of generation with **95%** power factor to a new section 4271003 is shown below in Table 4.

Table 4. Loadflow Analysis with Generation Connected as Negative Load

Section 4275297 (pcc):	
Load into section:	-195kW 67kVAR 11A
Voltage at pcc:	100.7% x 10.8kV
Length of new section:	917m
Section 4271003 (generator connection):	
Load into section:	-200kW 66kVAR 11A
Voltage at generator:	100.8% x 10.8kV

The voltage figures shown in Table 4 can be manually verified using the Thevenin equivalent circuit, with the assumption that the change in voltage is small. The R and X values for the substation should be subtracted from those values corresponding to the section being considered to take account of the automatic voltage controller (AVC) at the substation. This maintains a constant 10.8kV on the secondary winding regardless of load.

The percentage voltage rise at the pcc:

$$((1.007 / 0.998) - 1) \times 100 = \mathbf{0.902\%}$$

This figure must be below 1% in order to comply with item 1 in Table 1.

To verify compliance with item 2 in Table 1:

$$10\% \text{ of fault level: } 0.1 \times \mathbf{5.9MVA} = 595\text{kVA}$$

$$\text{Connected generator kVA: } 200 / 0.95 = \mathbf{211kVA} \text{ (less than } \mathbf{595kVA})$$

Connected kVA of the generator must be less than 10% of the fault level in order to comply.

3.2 Future Demand and Infrastructure

This section deals with the upgraded network, and examines two future scenarios. The first looks at 2005 (short term), with the predicted increase in current demand of 4% per year. The second makes the assumption that tidal flow turbines may be economically feasible by 2010 (medium term), and includes an additional increase in electrical demand (over the 4%) due to the widespread introduction of geothermal heating for residential properties.

Short Term (2005)

Table 5. Feeder Loads for 2005

Substation secondary nominal voltage: 21kV		
Maximum loads for Polranny substation:		
Winter	12.30	1.71MW
Winter	18.00	2.60MW
Summer		2.65MW

It is assumed that the percentage of the loads from the Achill feeder, the substation power factor and the load type are unchanged.

Distributed load from each feeder: 50.0 kVA

South Feeder

Table 6. Loadflow and Fault Analysis

Section 4275297 (chosen as pcc)		
Load into section:	8kW	3kVAR 0A
Voltage at pcc:	100.0% x 21kV	
Fault Levels:		
	line - line	3 phase
	(MVA)	(MVA)
Substation	68	78.6
4275297 (pcc)	22.8	26.4

All other conditions are as for Table 3.

Connection of Generator – Wind Turbines

The results of connecting **750kW** of generation with **95%** pf are shown in Table 7.

Table 7. Loadflow Analysis with Generation Connected as Negative Load

Section 4275297 (pcc):		
Load into section:	-741kW	250kVAR 21A
Voltage at pcc:	100.9% x 21kV	
Length of new section:	917m	
Section 4271003 (generator connection):		
Load into section:	-750kW	-247kVAR 21A
Voltage at generator:	101.0% x 21kV	

The percentage voltage rise at the pcc:

$$((1.009 / 1.00) - 1) \times 100 = \mathbf{0.9\%}$$

This figure must be below 1% in order to comply with item 1 in Table 1.

To verify compliance with item 2 in Table 1:

$$10\% \text{ of fault level: } .1 \times 26.4\text{MVA} = 2640\text{kVA}$$

Connected generator kVA:

$$750 / 0.95 = \mathbf{790kVA} \text{ (less than } \mathbf{2640kVA} \text{)}$$

Connected kVA of the generator must be less than 10% of the fault level in order to comply.

North Feeder

Table 8. Loadflow and Fault Analysis

All regulators on network set to neutral taps		
Section 4273864 (chosen as pcc)		
Distance from substation: 5.9 km		
Load into section:	45kW	15kVAR 1A
Voltage at pcc:	99.9% x 21kV	
Fault Analysis:		
	R (ohms)	X (ohms)
Substation	1.25	2.99
4273864 (pcc)	6.13	5.30
Fault Levels:		
	line - line	3 phase
	(MVA)	(MVA)
Substation	68.0	78.6
4273864 (pcc)	27.2	31.4

Connection of Generator – Wind Turbines

The results of connecting **900kW** of generation with **95%** pf are shown in Table 9.

Table 9. Loadflow Analysis with Generation Connected as Negative Load

Section 4273864 (pcc):		
Load into section:	-850kW	313kVAR 25A
Voltage at pcc:	100.8% x 21kV	
Length of new section:	2895m	
Section 4271050 (generator connection):		
Load into section:	-895kW	298kVAR 26A
Voltage at generator:	101.2% x 21kV	

By following similar calculations as performed for the south feeder, 900kW of generation is within voltage and fault level limits. The wind turbine generators (connected to each feeder) are located as shown in Fig. 4.

Medium Term (2010)

Table 10. Feeder Loads for 2010

Substation secondary nominal voltage:	21kV	
Maximum loads for Polranny substation:		
Winter	12.30	2.60MW
Winter	18.00	3.95MW
Summer	4.04MW	

The loads shown in Table 10 include the 4% increase in demand per year and an additional 25% increase in electrical demand in 2010 for geothermal heat pumps.

Distributed load from each feeder: 76.6 kVA

South Feeder

Table 11. Loadflow and Fault Analysis

Section 4275297 (chosen as pcc)		
Load into section:	12kW	4kVAR 0A
Voltage at pcc:	99.9% x 21kV	
Fault Levels:		
	line - line	3 phase
	(MVA)	(MVA)
Substation	68	78.6
4275297 (pcc)	22.8	26.4

All other conditions are as for Table 3.

Connection of Generator – Wind Turbines

The results of connecting **750kW** of generation with **95%** pf are shown in Table12.

Table 12. Loadflow Analysis with Generation Connected as Negative Load

Section 4275297 (pcc):	
Load into section:	-736kW 251kVAR 21A
Voltage at pcc:	100.8% x 21kV
Length of new section:	917m
Section 4271003 (generator connection):	
Load into section:	-750kW 247kVAR 22A
Voltage at generator:	101.0% x 21kV

By following similar calculations as performed for the south feeder under section 3.1, 75kW of generation is within voltage and fault level limits.

North Feeder

Generation from wind and tidal flow turbines are considered. The following results are maximum connection capacities for a wind powered or a tidal powered scheme considered separately, not connected together.

Table 13. Loadflow and Fault Analysis

Section 4273864 (chosen as pcc - Wind)		
Load into section:	68kW	22kVAR 2A
Voltage at pcc:	99.9% x 21kV	
Fault Analysis as for Table 8.		
Section 4274815 (chosen as pcc - Tidal)		
Distance from substation:	14.4 km	
Load into section:	0kW	0kVAR 0A
Voltage at pcc:	99.9% x 21kV	
Fault Analysis:		
	R (ohms)	X (ohms)
Substation	1.25	2.99
4274815 (pcc)	13.13	8.60
Fault Levels:		
	line - line	3 phase
	(MVA)	(MVA)
Substation	68.0	78.6
4274815 (pcc)	14	16.2

Connection of Generator – Wind Turbines

The results of connecting **950kW** of generation with **95%** pf are shown in Table14.

Table 14. Loadflow Analysis with Generation Connected as Negative Load

Section 4273864 (pcc):	
Load into section:	-875kW 338kVAR 26A
Voltage at pcc:	100.8% x 21kV
Length of new section:	2895m
Section 4271050 (generator connection):	
Load into section:	-945kW 315kVAR 27A
Voltage at generator:	101.2% x 21kV

Connection of Generator – Tidal Turbines

The results of connecting **400kW** of generation with **95%** pf are shown in Table15.

Table 15. Loadflow Analysis with Generation Connected as Negative Load

Section 4274815 (pcc):	
Load into section:	-339kW 132kVAR 11A
Voltage at pcc:	100.8% x 21kV
Length of new section:	200m
Section 4271060 (generator connection):	
Load into section:	-400kW 131kVAR 11A
Voltage at generator:	100.8% x 21kV

It can be shown that either of the above generation schemes will comply with voltage and fault level limits, by following the calculations detailed in section 3.1.

3.3 Energy Generation and Demand

This section compares the amount of energy provided by the connected generation with the energy demand for the island on an annual basis.

Current Situation

Energy Demand:

Electricity 12,271 MWh
Fossil Fuels 11,776 MWh
Fossil Fuels 54,500 MWh (residential)
ESB provide a figure of 11,000 MWh of electricity for the Achill Island feeder.

Energy produced by one Lagerwey LW 30 250kW variable speed wind turbine modified to provide a maximum output of 200kW with a power factor of 95%:

Electricity 828 MWh

Percentage of annual energy demand displaced (using ESB figure for electricity demand):

$828 / 77,276 = 1.07\%$

2005

Energy Demand:

Electricity 12,374 MWh (+4% p.a.)
Fossil Fuels 13,246 MWh (+4% p.a.)
Fossil Fuels 54,500 MWh (residential)

The increase in demand for fossil fuel energy is assumed to follow a similar trend as that for electricity, however the energy audit noted that there is a gradual decline in the use of turf for space heating and hot water requirements within residential properties, with this being replaced by more efficient oil fired heating. The figure for residential fossil fuel use is therefore left unchanged.

Energy produced by three Lagerwey LW 30 250kW variable speed wind turbines with a power factor of 95% and connected to the south feeder:

Electricity 2651 MWh

Energy produced by four Lagerwey LW 30 250kW variable speed wind turbines modified to provide a maximum output of 225kW each, with a power factor of 95% and connected to the north feeder:

Electricity 3414 MWh

Percentage of annual energy demand displaced (using ESB figure for electricity demand):

$6065 / 80,120 = 7.56\%$

2010

Energy Demand:

Electricity 19,792 MWh (see below)
Fossil Fuels 16,116 MWh (+4% p.a.)

The increase in demand for electricity includes the figure of 4% per year and an additional electricity demand as a result of a hypothetical situation where the residential demand for fossil fuels for heating purposes is replaced by energy provided by geothermal heating systems, with an upgrade in fabric insulation.

Energy produced by three Lagerwey LW 30 250kW variable speed wind turbines with a power factor of 95% and connected to the south feeder:

Electricity 2651 MWh

Energy produced by four Lagerwey LW 30 250kW variable speed wind turbines modified to provide a maximum output of 237.5kW each, with a power factor of 95% and connected to the north feeder:

Electricity 3439 MWh

Percentage of annual energy demand displaced (using ESB figure for electricity demand):

$6090 / 35908 = 16.96\%$

If the wind turbines connected to the north feeder were substituted with tidal flow turbines, the annual energy output from a generating capacity of 400kW would be:

Electricity: 686 MWh

4. DISCUSSION OF RESULTS

From the results shown above it is clear that the electricity distribution network in its current form is unable to accept significant amounts of generation due to steady state voltage increases. The primary reason for this is that these networks are designed for low and sparsely distributed loads, and therefore high impedances exist between the extremities of supply and the feeder substation. A maximum connected capacity of 200kW from a wind energy generator is small in comparison to the wind resource available in this area. There is little opportunity at the present time for displacing any significant amount of energy consumption with renewable energy fed into the local electricity grid.

The upgrading of the network increases the connected capacity to 1650kW, as each feeder can be treated separately and advantage taken of the doubling of supply voltage. This figure increases to 1700kW (from wind) or 1150kW (from wind and tidal) as more local demand is available to absorb generation. It is noted that the 400kW tidal scheme is not as favourable in this case, as the greater distance from the connection point to the substation reduces the

amount of generation capacity that can be absorbed due to steady state voltage increases. It also provides a lower annual energy yield when compared to a 200kW wind powered generator.

The situation can be marginally improved by increasing the reactive power consumption of the generator, however ESB encourage all embedded generators to operate at 95% power factor. A greater generation capacity could be connected at a point on the network closer to the substation where impedances are naturally lower and a greater percentage of local load can absorb the power input. However this will not always coincide with the most favourable positions for siting generation plant.

In all of the scenarios considered here the allowable connected capacity is greater than the minimum demand, leading to reverse power flows through the substation transformer during these periods. However most commonly-used transformer AVCs operate perfectly well in this situation [7]. It is likely that the capacity of the substation would also be upgraded along with the feeders themselves, to serve the projected increase in demand.

Besides the criteria for connection of embedded generation considered here, there are other network effects to be considered. ESB places limits on voltage flicker which may be caused by wind turbulence, tower shadow and the switching on and off of generators if these operations are not controlled with the correct equipment/operating procedures. This is especially true in areas where fault levels are low as in this case. A sudden loss of generation will cause a step voltage change, the tap changer in the substation will take a little time to increase the voltage to compensate. Variable speed wind turbines fitted with a power electronic interface between an induction generator and the network were chosen for energy calculations in this study as they are likely to cause few problems with voltage flicker and fault level contribution. A larger number of lower power output generators for a given total capacity are also superior with regard to short-term voltage variations [7].

These and other variables including harmonic injection and the risk of islanding are discussed in the relevant distribution and grid codes [8,9].

5. CONCLUSIONS

This study highlights the limitations of a typical rural electrical distribution network in quantifiable terms, with respect to the connection of generation plant powered by renewable energy sources. Electrical networks of this type provide a barrier to the large scale deployment of renewable energy, often in areas where significant resource exists. The cost of connection to necessarily higher voltage is a limiting factor in the economic viability of multi-megawatt schemes. For the energy demand to be significantly displaced through electrical generation feeding into the local network, a dedicated 20kV feeder would be required. Offshore wind turbines are currently being considered within the Altener contract to ultimately displace all energy consumption, connected at the 33kV level.

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