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Modelling a reliable wind/PV/storage power system for remote radio base station sites without utility power

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Abstract

The development of photovoltaic (PV) cells has made steady progress from the early days, when only the USA space program could afford to deploy them, to now, seeing them applied to roadside applications even in our Northern European climes. The manufacturing cost per watt has fallen and the daylight-to-power conversion efficiency increased. At the same time, the perception that the sun has to be directly shining on it for a PV array to work has faded.

On some of those roadside applications, particularly for remote emergency telephones or for temporary roadwork signage where a utility electrical power connection is not practical, the keen observer will spot, usually in addition to a PV array, a small wind-turbine and an electrical cabinet quite obviously (by virtue of its volume) containing a storage battery. In the UK, we have the lions share (>40%) of Europe's entire wind power resource although, despite press coverage of the "anti-wind" lobby to the contrary, we have hardly started to harvest this clean and free energy source.

Taking this (established and proven) roadside solution one step further, we will consider higher power applications. A cellular phone system is one where a multitude of remote radio base stations (RBS) are required to provide geographical coverage. With networks developing into the so called "3G" technologies the need for base stations has tripled, as each 3G cell covers only 1/3 the geographical area of its "2G" counterpart.

To cover >90% of the UK's topology (>97% population coverage) with 3G cellular technology will requires in excess of 12,000 radio base stations per operator network. In 2001, there were around 25,000 established sites and, with an anticipated degree of collocation by necessity, that figure is forecast to rise to >47,000. Of course, the vast majority of these sites have a convenient grid connection.

However, it is easy to see that the combination of wind and PV power generation and an energy storage system may be an interesting solution for the more rural and remote applications – particularly those where an electrical supply is not available or practical – and this paper attempts to explore the current practicalities of such a power generation solution for those cellular phone base stations.

Keywords: Wind; Photovoltaic (PV); Radio base stations; Remote sites; Off grid; Hydrogen storage

1. Introduction

The development of photovoltaic (PV) cells has made steady progress from the early days, when only the USA space program could afford to deploy them, to now, seeing them applied to roadside applications even in our Northern European climes. The manufacturing cost per watt has fallen and the daylight-to-power conversion efficiency increased. At the same time, the perception that the sun has to be directly shining on it for a PV array to work has faded.

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entire wind power resource [1] although, despite press coverage of the “anti-wind” lobby to the contrary, we have hardly started to harvest this clean and free energy source.

Taking this (established and proven) roadside solution one step further we will consider higher power applications. A cellular phone system is one where a multitude of remote radio base stations (RBS) are required to provide geographical coverage. With networks developing into the so called “3G” technologies the need for base stations has tripled, as each 3G cell covers only 1/3 the geographical area of its “2G” counterpart. In the UK (if not elsewhere), the competition between service providers is both intense and fiercely cost cutting. By October 2003 [2], the largest four mobile phone operators shared the market in a very approximate 35/25/25/16% proportion and that market was, to all intents and purposes, 100% penetrated – 50.2 million active consumer accounts versus the 58.8 million population of the UK. Having paid huge sums to the government for the operating licences the downward pressure on capital and operational expenditure is constant, whilst the fierce competition restricts most cooperation on sharing an infrastructure.

To cover >90% of the UK’s topology (>97% population coverage) with 3G cellular technology will requires in excess of 12,000 radio base stations per operator network. In 2001, there were around 25,000 established sites and, with an anticipated degree of collocation by necessity, that figure is forecast to rise to >47,000 [3]. Of course, the vast majority of these sites have a convenient grid connection.

However, it is easy to see that the combination of wind and PV power generation and an energy storage system may be an interesting solution for the more rural and remote applications – particularly those where an electrical supply is not available or practical – and this paper attempts to explore the current practicalities of such a power generation solution for those cellular phone base stations.

2. The load

2.1. Electrical

The load that has to be supplied by the power system is, naturally, continuous on a 24 × 7 × 52 basis and comprises the cell transmission equipment, microwave link and any required energy for ambient control—heating and cooling. The equipment has traditionally been 48 V dc with a 4 h battery back-up but recent trends, both technically and commercially driven, have seen the introduction of ac powered loads (requiring UPS) and the acceptance of much shorter battery autonomy times (as low as 20 min). Note that the availability of the mains power in the UK is such that grid failures lasting longer than 20 min in the South East urban conurbations are, statistically, more than 6 years apart.

The size of the radio transmission (RT) load has been steadily falling and is forecast to fall further. Originally the forecast power consumption for 3G RT equipment was in the order of 10 kW and, with the colocation of 2G for an overlap period, many operators planned for up to 15 kW per base station. In reality, the loads have not been seen to be higher than 5 kW for a fully populated base station. For the future, it is safe to assume that power-to-transmission power efficiency will steadily improve—bearing in mind that the aerial power is in the order of tens of watts rather than hundreds. An overall design figure (including cooling) of 4 kW for a high power 3 × 3 sector aerial system is now expected to be conservative. It should be noted that when planning engineers were anticipating 12–15 kW for the RT and microwave load the mechanical cooling added a further 4–5 kW, resulting in each site requiring up to 20 kW of supply capacity.

2.2. Mechanical

The load has also been influenced by the mechanical solution to base station deployment. Traditionally the RBS looked as that illustrated in Fig. 1, a “walk-in” cabin, and most included mechanical cooling via some form of air conditioning plant. With local opposition increasing, fewer planning restrictions on enclosure volumes below 2.5 m^3 and the new availability of “outdoor enclosures” the face of the UK’s RBS rollout program has changed.

Fig. 2 shows a typical outdoor enclosure with, in this case, 16 kW of dc power, empty space for the RT equipment and inbuilt heat exchanger in the door.

Some operators, for reasons of both capital cost and operational expenditure, historically decided to take technical “risks” in two significant areas both related to cooling.

The “perfect” solution addresses both the RT electronics and the battery, and that are temperature and humidity control via some form of precision air conditioning. This avoided the need for dragging in fresh-air (with damp and air-borne contaminant problems) and maintained the battery temperature at 20–25 °C for optimum service life. Some operators

Fig. 1. RBS cabin and mast.

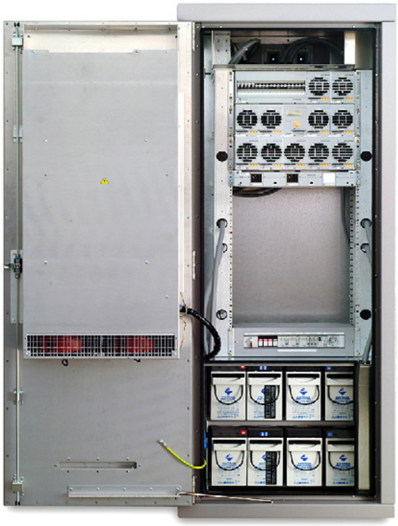

Fig. 2. Outdoor power/RT enclosure. *Courtesy*: Emerson Network Power.

used fresh-air cooling for the cabin and fitted heat exchangers to the RT plant whilst some went “half-way” and ignored humidity control, running the risk of condensation or static. At the same time, the RT equipment itself was becoming much less sensitive to temperature fluctuations, etc.

An important cost factor in the case “against” air conditioning was the minimum of two maintenance visits per year. It is also worth noting that some operators installed commercial “split” systems (rather than industrial equipment designed for continuous duty) and the need for visits increased due to increased incidence of breakdowns, etc.

The result of all of these pressures and experiences has resulted (assisted by our climate) in a widespread abandonment of cabins in favour of enclosures and an acceptance that batteries will have to be sized and maintained with a wide range of operating temperatures in mind. Battery autonomies and anticipated service life have both been shortened. Simple and rugged air-to-air heat exchangers maintain a reasonable 6–8 K temperature difference between the outdoor ambient and the enclosure interior but that still leads to accelerated internal battery corrosion during the summer months.

2.3. Total load for modelling

The UK weather is “mild, wet and windy” and the requirement for cooling is driven by the size of the enclosure (solar gain), exposure of the site (prevailing wind, etc.), the ambient temperature and the internal load. Temperature modelling for the South Coast of England shows that up to 4 kW of power can be housed in a typically sized heat exchanged outdoor enclosure without the internal temperature exceeding 45 °C in the maximum (July) ambient temperature. As you work northwards the installed capacity can rise to 5 kW by the time you reach Edinburgh.

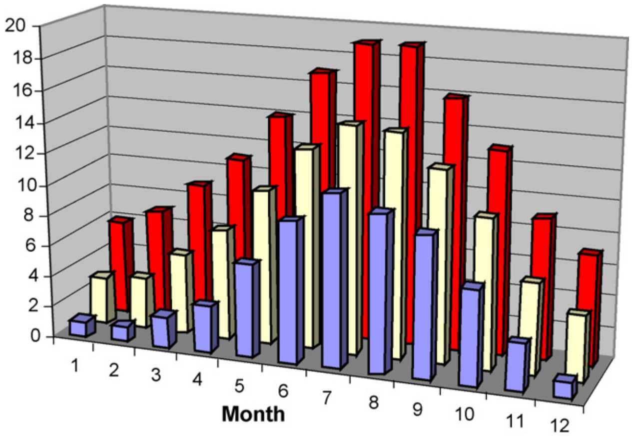

Fig. 3. Daily average temperature in Edinburgh (°C).

Heating is rarely required, as can be inferred from Fig. 3, which shows (back row to front) the average daily maximum, daily average and the average daily minimum ambient temperature by months January–December [4].

The trends of lower power for both the electronic loads and any associated climate control are expected to continue falling. Some industry sources are predicting the RT power to fall from the present 3.5 to 2 kW by 2007 and for this paper, we will use 4 kW as the total continuous demand.

So it can be seen that in the space of 3–4 years the anticipated peak power demand per RBS site has dropped from 20 kW to less than 4 kW.

3. Environmental impacts

We should never underestimate the environmental impact of any human activity that is continuous in nature. The ability to use your mobile phone at “any time” means that the network must be powered up at “all times”. The 4 kW per base station that we have chosen to model represents 35 MWh year^{-1} (126 GJ) which would release 12.6 tonnes of CO_2 if generated by natural gas. Taking the four major networks’ radio base stations together totals 600,000 tonnes of CO_2 per year. It is clear that the faster the RT power demand is reduced the better for all concerned; not least the operators who have to pay the electricity bill whilst we all demand cheaper call charges.

4. Power options

4.1. Mains power

Obviously, all costs considered, the most viable option is a mains connection with a relatively short storage 48 V battery. Any ac powered equipment can be powered via a dc–dc converter from the 48 V common rail and inverted to ∼230 V or via a dedicated UPS with an integral battery. However, any special connection requiring a new cable installation over 500 m long is becoming increasingly expensive.

4.2. On-site non-renewable generation

Such as combusting a fossil fuel, most likely diesel or propane, in a reciprocating engine to drive a generator and produce electrical energy. No battery storage would be necessary. The fuel would be stored on-site (if a gas pipeline were available you would expect an electrical supply as well) so a delivery method and route has to be practical and planned in advance. Note that our 4 kW continuous load (126 GJ year^{-1}) would consume around 2600 imperial gallons of diesel oil in one year (10 tonnes, 73 barrels). A gas engine would be cleaner but for both fuels the continuous rating would require regular maintenance visits. Unless two sets were installed (in $N+1$ redundant configuration) maintenance would necessitate a site shutdown.

4.3. On-site renewable generation

In theory, at least we can include here the concept of a fuel cell supplied with hydrogen gas. Whilst the power range is within current successful technology continuously operating a 4 kW fuel cell on other, less pure, fuels (e.g. natural gas) is not yet proven. However, our application has little use for the waste heat (this also applies to Section 4.2 above) and, as we shall see, the matter of fuel delivery and storage volume may be an issue. However, in this option, we are mainly looking at wind and solar electric (PV), either solo or in combination but in both cases with on-site storage to overcome the problem of “intermittence”.

5. Intermittence of wind and PV generation

One of the largest problems in all sustainable energy technology application is matching the generation capacity to the load. The case of the RBS has one advantage—the load is totally predictable and continuous. In the case of several renewables, wind and PV included, this load matching problem is exacerbated by the intermittence of the generation periods. In some cases, this is highly predictable, e.g. diurnal for tidal power or rather less predictable, as is the case with wind power.

5.1. Wind power

Power from the wind depends upon the swept area of the turbine blades and the cube of the wind speed. Each design of turbine can be optimised for the actual site conditions and prevailing wind. Wind turbine design is such that power is generated between a minimum (cut-in) and a maximum (shut-down) wind speed. It is interesting to note that planning problems for on-shore wind turbines have encouraged the deployment of off-shore installations. Not only is the initial capital cost increased but also the risk of it being “too windy” (in the depths of winter when the load is at a peak) is increased, with no power output as a result.

Opponents of wind power often claim that they are “low efficiency” generators. This is to confuse two issues:

- the difference between the rated power of the turbine operating for a continuous period with the actual power generated by the intermittence of the wind speed at a given site;
- the “fuel” is free, and therefore, the “efficiency” is 100% (in a classic “fuel input” versus “energy output”).

In very round terms, a given turbine will generate between 30–40% of its “rated output” over a year, depending upon the site wind conditions, e.g. a 15 kW turbine could produce 130 MWh over 1 year (8760 h). In actual (on-shore) service, it could be expected to produce around 35 MWh—an “efficiency” of 27%, according to your point of view. A turbine of this rating would be 9 m diameter. It is worth mentioning that medium power machines (say <20 kW) do not generally have a shut-down wind speed requirement but continue to supply rated power.

To appreciate the intermittence of the wind, look at Fig. 4. This shows the daily kWh generated by a small 7.5 kW turbine sited in a hillside location in Wales with real wind speed data (hourly average). The horizontal line represents a target continuous load of 1 kW. Despite the region being one of the best wind resource locations in Europe it can be seen (circled) that a lack of wind resulted in a low power output for 10 days.

5.2. Photovoltaic generation

There is no confusion about the intermittence of PV—it requires daylight. It is important to note, however, that it does not require “sunshine”; it is just less “efficient” at gathering the energy in overcast conditions. The energy from the sun falls at our latitude at a peak of 1 kW m^{-2} which corresponds to an insolation annually of 1000 kWh m^{-2} of diffused solar

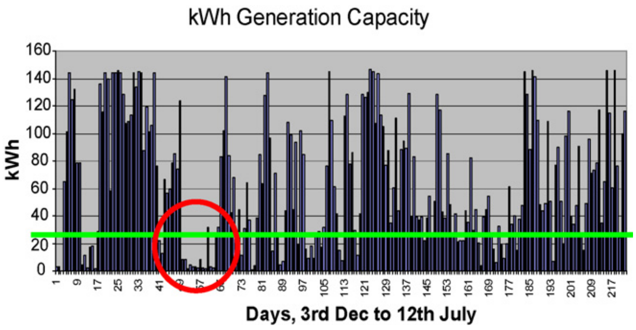

Fig. 4. A 7.5 kW turbine daily output.

radiated energy [5]. The annual average conversion efficiency of commercial PV cell arrays is around 12%, resulting in a reliable output figure of 120 kWh m^{-2}.

It has to be said that until a mass-production effect pushes the cost of PV cells down they remain commercially unviable for most applications above a few hundred watts. Both the cost per watt and conversion efficiency will improve with the research and development that is taking place and there is no doubt that solar PV will play a valuable part in a post-fossil fuel energy plan. In fact, the oil companies are amongst the largest investors in PV technology.

6. Energy storage

One of the key elements in most fields of renewables is the question of energy storage. The storage is required to bridge the gap between the energy being available, e.g. the wind blowing hard (or not), and the instantaneous load consumption. Our RBS is a rather extreme example of this because no diversity (in multiple loads) can be assumed.

The form of storage has traditionally been “electro-chemical”, lead–acid recombination batteries of the VRLA type. This is a low tech, rugged, well proven and predictable solution but more suited to a few hours autonomy rather than several days.

The other forms of storage are “chemical” in the form of fuel for combustion (or feeding fuel cells) and “mechanical” in the forms of inertia flywheels or potential energy of compressed air. As Fig. 5 shows, the energy density of these options (in Wh kg^{-1} and Wh l^{-1}) is very different and it is clear why liquid fossil fuels are so convenient. It also has to be said that these comparisons include all of the energy stored, not all of which is recoverable for constant power loads.

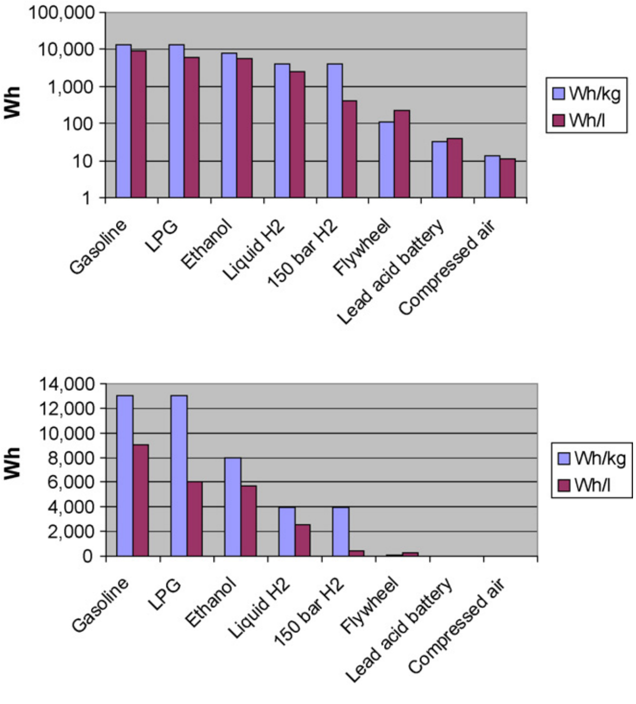

Fig. 5. Energy storage density. Top: logarithmic scale; bottom: linear scale.

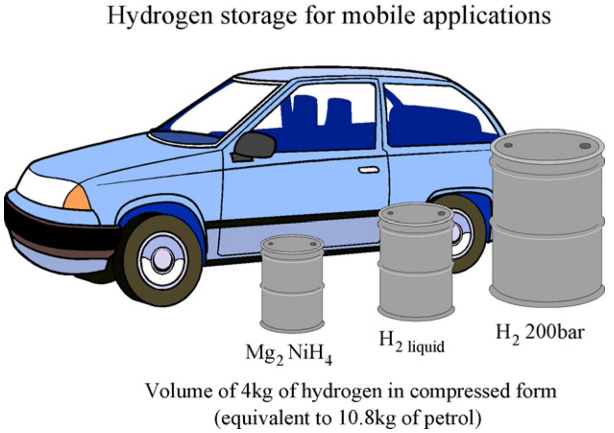

Fig. 6. H_2 low energy density.

For the hydrogen options note that compression to 150 bar consumes 10% of the energy content and it still needs 25× the volume of gasoline for the equivalent capacity storage, whilst liquefaction of H_2 consumes 30% of the energy content and has rather more storage infrastructure implications. As a general consideration for the future “hydrogen economy” consider that a road tanker carrying H_2 at 200 bar would consume all of the energy in its load to make a 550 km delivery [6], the implication being that decentralised production of H_2 and (short) pipeline distribution is to be preferred. Fig. 6 shows the technical challenges facing the mobile fuel cell market for only 4 kg of fuel; the first thing to do would seem to be to make cars with much lower performance and a more efficient power system.

The reason for the historical dominance of the diesel generator for standby duty is clearly illustrated by the comparison shown in Fig. 7.

One barrel of Grade A1 distillate oil (left) will provide 540 kWh from a diesel genset. A battery (rear) to do the same duty would occupy 40 m^3 and weigh 25 tonnes (about the same as the genset) whilst H_2 (at 150 bar) is shown in comparison.

Fig. 7. Energy storage comparison.

7. Practical RBS solutions

It would appear that, regardless of how the power is generated, that there are few (currently practical) commercial options other than a standby diesel generator to provide long-term autonomy, e.g. for longer than 24 h. However, a battery is still required to maximise the collection of the wind and/or PV power and that battery can be optimised to reduce the start/run requirement on the generator to a minimum.

The RBS has one feature that might lend itself to our purpose—the mast. Obviously replaced by a suitably designed alternative, it could be proposed that the mast supports a wind turbine and, facing on the south side, a PV array.

There might be a problem to overcome with the (two or three) turbine blades passing in front of one or more of the sector aerials but the position of the blades are measurable and the digital transmission algorithms could, no doubt, be adjusted to suit.

The generation capacity we need to install would be 8.76 MWh year^{-1} per kW of RT load, so let us take two cases: 4 kW now and 2 kW by 2007.

7.1. *Total load = 4 kW*

This would need 35 MWh year^{-1} and autonomy of 1 MWh to see it through 10 days, if only one power source was available. If we assume that a 15 kW, 9 m diameter, turbine is applied the mast would need to be in the order of 15 m high (not dissimilar to existing mast heights). Such a turbine could be expected to generate between 32 and 45 MWh depending upon the site conditions. Bearing in mind the "remote" nature of sites we are considering the upper figure will be achievable.

If the PV array were to be 2 m wide (which is probably optimistic due to visual problems with planning authorities) we could install 25 m^2, which would generate 3 MWh year^{-1} but probably as little as 4 kWh in a "worst case" 24 h period in the winter. This is only enough to drive the load for 1 h (1/24th), hardly making a significant contribution to the power system resilience.

To provide the 1 MWh autonomy from a battery is impractical (80 m^3 and >40 tonnes). It is clear that a small 4 kW diesel generator is all that is required – with, say – a 96 kWh battery to give 24 h autonomy for 4 kW load. The on-site fuel store need be no more than 350 l.

7.2. *Total load = 2 kW*

Treated as the same as above: This would need 18 MWh year^{-1} and autonomy of 0.5 MWh to see it through 10 days, if only one power source were available. If we assume that a 7 kW, 5 m diameter, turbine is applied the mast would need to be in the order of 12 m high. Such a turbine could be expected to generate between 16 and 22 MWh depending upon the site conditions. If the PV array were to be 2 m wide we could install 20 m^2, which would generate 2.4 MWh year^{-1} but probably as little as 4 kWh in a "worst case" 24 h period in the winter. To provide the 0.5 MWh autonomy from a battery is impractical (40 m^3 and 20 tonnes).

It is still clear that a (even smaller) 2 kW diesel generator is all that is required – with, say – a 48 kWh battery to give 24 h autonomy for 2 kW load, and a diesel fuel store of <175 l.

8. Conclusions

The application of PV is not technically (or commercially, yet) viable for this application. A 24 × 7 constant load is not suited to PV technology. The size of the array is limited and the possible contribution to the power demand is small.

Wind power is technically viable and has some practical possibilities being integrated with the radio mast. Short-term autonomy is best provided by a VRLA battery. The longer-term intermittence of the wind demands a back-up power supply best provided by a diesel generator. The battery will minimise the start/run demand on the diesel engine, which in turn will minimise the required size of the battery storage capacity.

Other forms of energy source could, at some time in the future, incorporate local hydrogen production using the "excess" wind power to electrolyse H_2 from water (possibly from rain collection). The hydrogen thus produced would be stored on site – perhaps in an underground tank or inside the mast to minimise visual impact – and used to generate power via a fuel cell.

The key is to find an RT technology that uses less power. In all forms of future energy calculations, "conservation" is the first thing to invest in "generation" decisions and investment must always come later.

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