Can Solar Power Help Providing Broadband Cellular Coverage in Extreme-Rural Sweden?

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EXECUTIVE SUMMARY

The Swedish government has expressed the goal that 90% of households and companies have access to at least 100 Mbit/s. Indications are that while fulfilling this target, 7-10% will remain without a fast broadband solution, the majority of which, not surprisingly, live in rural regions. Meanwhile, the European Commission has declared the goal that all EU-citizens will have access to internet speeds of at least 30Mbit/s by the year 2020. How will Sweden be able to offer the rural 10% of its citizens (about 430 000 households) a 30 Mbit/s connection by 2020, with the two main technical alternatives: satellite and mobile broadband? And moreover, how will Sweden be able to provide stronger mobile broadband for people on the move, in other places than where they live or work?

In order to change the underlying business cases that reign today's market structure there needs to be a technical break-through that enables a radically more cost-efficient infrastructure that is capable of delivering mobile broadband of large coverage areas. A dominant cost driver is the need for electricity to power the network equipment. In rural regions where the electricity grid does not naturally reach all locations this cost driver is more pronounced than in other regions. In this report we present an initial assessment of the possibilities and challenges with powering radio nodes in extreme rural regions with solar power. We collect a variety of data that puts the possibilities and limitations in a new perspective.

First, for every location in the country there is exactly one areal concession holder that has the obligation to connect a new customer to the electricity grid if that customer demands so, but also has to charge the new customer for the actual costs of the new connection. These costs are higher for more remote locations. Not only would a full local energy supply eliminate the costs for using the electricity network but also the reliability of the local distribution grid at remote locations could be better controlled.

We further show that today's macro base stations need a power supply of 500-1000 W (continuous) even without radio traffic being present just to guarantee operation and coverage. In the rural regions the yearly energy use will be dominated by this figure as the traffic load is low. Furthermore, we show projections by Alcatel-Lucent that illustrate how base station's energy consumption will reduce to below 200W within a few years. For the low-load rural regime this report therefore coins the target of the 100W macro base station as an enabler of low-cost rural radio coverage.

We show figures that illustrate the availability and potential of solar power in Northern Sweden. Based on solar power data from Skellefteå, our conclusions are twofold. On one hand, the yearly energy consumed by the target 100W base station can be supplied by an 7 m² local PV installation. On the other hand, large batteries are needed to bridge the absence of solar power during a 3-month period in the winter. While the first provides a cost-efficient enabler to power a base station, the second still comes with prohibitively high cost, given today's battery prices. Wind power may be used to reduce the need for batteries and hence reduce the cost.

Finally, we identify two main emerging technologies that carry the potential to reduce a base station's energy consumption below the 100W continuous target. First, the use of large antenna arrays which is being developed mainly for high capacity urban environments can also provide beamforming gains that potentially and hugely reduce the energy needed to be radiated at the antenna. Second, today's 4G LTE standard specifies a large number of control signals that are continuously radiated by a standard-compliant base station. Reduction of these transmissions, especially in the low-load rural regime, can reduce the base station's energy consumptions significantly. An ultra-lean design in a new standard specification can provide the basis for this.

This report concludes therefore with a list of potential and necessary further research that includes 1) dimensioning of battery storage when using a combination of solar power and wind power, 2) dimensioning the radio network under tight energy-constraints per node, 3) quantify the energy-reducing potential of large beamforming antenna arrays, 4) redesigning the radio protocol with the goal to reduce downlink signalling (broadcast, synchronization channels and pilot signals).
1 INTRODUCTION: CELLULAR RADIO COVERAGE IN SWEDEN

Just a handful of technologies have changed lifestyle as much as mobile broadband has over the last years. Steady connectivity has changed our habits, boosted our productivity, informed us and enabled us to participate as never before. By rolling out mobile broadband much has been achieved. However, not everybody is included in this development. In fact, there is evidence that fixed and mobile broadband are being withdrawn from surface and people in rural regions, instead concentrating on providing more and better services in the major cities and urban areas.

Figure 1 shows the population density in municipalities of the Nordic countries and illustrates how largely population density differs in various parts of Sweden. This report addresses the broadband connectivity in the municipalities with lowest population density, and not only in their villages and habitated locations, but truly everywhere. An important obstacle appears to be a sufficiently cheap energy-supply for the radio network that should support these services.
1.1 Revocation of the Swedish fixed broadband network

In rural Sweden, Telia has been taking the first steps of revocation of the fixed telephony infrastructure (in its "Teknikskifte"-project) in areas where pursued maintenance of lines based on telephone poles were considered too expensive. Recently, a second phase in this development has started, a phase where remote central stations that serve end users with both voice and DSL services, are being decommissioned [1][2]. Users in these regions will now be solely depending on reliable availability of mobile networks. Initial feedback from customers reveals a huge amount of complaints on coverage and reliability.

This cost- and change-driven development illustrates the motivation and structure that govern today's market-dominated fixed-network deployment decisions. Even worse, we can expect these market-driven factors to increase. Labour costs for maintenance will increase, while at the same time potential operator revenues decline. This trend will push the border closer and closer towards urban coverage only over time.

1.2 What about the mobile broadband network?

The notion of broadband coverage is intricate and full of nuances. With certain operators committing to areal 4G coverage of 90%, huge differences in perceived service-coverage between urban and rural regions is notable.

A recent survey by the Swedish regulator PTS [3] reveals huge differences in today's service quality. For mobile telephony the statement "I can call without technical interruptions" was subscribed by 76% of the urban citizens while just 60% of rural inhabitants answered confirming. For mobile broadband, the statement "I can surf the web", was confirmed by 78% of urban and just 55% of rural citizens.

In another survey by PTS [4] these figures are confirmed: The Stockholm region has a 99% 4G-residential coverage with a signal strength allowing both indoors and outdoors. For the Norrbotten region residential coverage numbers are 89% (outdoor reception) and 82% (indoor reception). These numbers are a clear indication how much weaker rural networks are being designed compared to urban networks. The associated figures for areal 4G-coverage are for the Stockholm-region 99% (outdoor coverage) and 88% (in-car coverage) and for the Norrbotten-region 15% (outdoor coverage) and 7% (in-car coverage).

Apparently there are two problems that need to be addressed:

1. **Missing coverage**: Large rural areas in Sweden are not covered at all. Operators do not even claim coverage in these areas.

2. **Weak coverage**: In rural regions, areas with operator-declared coverage have typically much weaker coverage than corresponding areas in urban regions.

Figure 2, taken from Telia's website [5], shows the coverage promised and committed to by Telia. The online tool allows for the choice of three levels of service. The grey spots in the Figure indicate locations where coverage for a 3G or 4G service with at least 2 megabit per second is "very good (calling/surfing indoors and outdoors is likely possible)". This is the coverage quality we have come to get used to in the urban regions of the country. Anywhere else, quality reduces to "good", "basic", or "missing", all of which come with quality disruptions we are not used to in the cities. The Figure suggests how coverage quality decreases as soon as people leave the places where they use to live or work, and provides understanding and credibility to the experiences in the PTS report mentioned above.
The grey spots indicate locations where coverage for a 3G or 4G service with at least 2 megabit per second is "very good (calling/surfing indoors and outdoors is likely possible)". This is the coverage quality we have come to get used in the urban regions of the country. Anywhere else, quality reduces to "good", "basic", or "missing", all of which come with quality disruptions we are not used to in the cities.

1.3 National and European goals and regulatory activities

In light of the above, there is reason for concern that today's digital divide will widen. The Swedish government has declared the goal that 90% of households and companies have access to at least 100 Mbit/s. Indications are that this goal will be reached mainly through the deployment of optical fiber networks (89-92 %), along with just 1% in (near-)urban areas through deployment of upgraded mobile networks [4]. These indications, hence, leave 7-10% without fast broadband solutions, the majority of which, not surprisingly, live in rural regions.

Meanwhile, the European Commission has declared the goal that all EU-citizens will have access to internet speeds of at least 30 Mbit/s by the year 2020, which would include the above remaining 7-10%. How will Sweden be able to offer the rural 10% of its citizens (about 430 000 households) a 30 Mbit/s connection by 2020, with the two main technical alternatives: satellite and mobile broadband?

Ironically, when people migrate from rural areas to more urban areas the figures above improve. Hence, unfortunately urbanization is a solution that brings the above goals a step further. While the Swedish government also has objectives for a prosperous rural regional development it is apparent that other coverage measures must be developed and used than the ones above. Today, coverage measures relate to people and the connectivity they experience in places where they live and work. Instead, measures should relate more to the areal dimension and relate to people's mobility patterns, to routes and areas they occasionally visit and to the connectivity offered there.
1.4 Bluelight and security services

Bluelight services are today provided by a Tetra network operating on 450 MHz. This network has a better coverage natively as it operates in the 450 MHz band. The main reason of operating a separate network for bluelight services has traditionally been that this approach is the only way to guarantee confidentiality, capacity and security, key requirements for these kind of services.

There are two main disadvantages in operating a separate network. Not only is, obviously, the cost one of these disadvantages, but more importantly, the increasing difficulty in keeping up with technical innovations in the area is becoming apparent. An increasing flow of reports provides examples of the police using commercial mobile services in their daily work tasks. The historical reasons for keeping these networks apart have started to disappear due to the ongoing technical evolution.

Network slicing is a key emerging technology that will enable virtualization of networks in a near future, thereby separating their use and functionality. In other countries the traditional setup is increasingly being questioned. The UK has decided to start a transformation and gradually shut down their Tetra networks ("LiTra"). Such a move represents substantial savings but will eventually put increased coverage requirements on the shared underlying mobile networks.

1.5 Vision of a future architecture

True areal broadband coverage is limited by the business case and the lack of a clear market model. Mainstream telecom business to a large extent ignores the issue and the silence should not come as a surprise. Not only is it well known that the building cost of a network is related to the area to be covered, but more importantly, as recognized in [6], "the real barrier to rural deployment is the lack of potential revenue per square mile. The revenue potential for a wireless carrier in a major urban center is $248,000 per square mile and year of service. By contrast, in the least densely populated areas, the potential revenue per square mile drops as low as $262 per square mile and year." There simply is no good commercial reason today to connect the un-connected part of the world's population, and hence little substantial and necessary research is carried out.

Table 1 illustrates how many base stations would be needed to cover Norrbotten, the northernmost Swedish administrative region. The Table also lists the number of inhabitants, a key parameter in the operator's market assessment and their prospected ROI, return on investments.

Table 1: Minimum number of base stations needed to provide coverage in the fourteen municipalities constituting the northernmost Swedish province: Norrbotten. This number reduces quickly as the cell-radius increases.

<table>
<thead>
<tr>
<th>Municipality</th>
<th>population</th>
<th>area (km²)</th>
<th>number of stations if r=3km</th>
<th>number of stations if r=5km</th>
<th>number of stations if r=10km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arjeplog</td>
<td>2887</td>
<td>14494.16</td>
<td>620</td>
<td>224</td>
<td>56</td>
</tr>
<tr>
<td>Arvidsjaur</td>
<td>6471</td>
<td>6126.30</td>
<td>263</td>
<td>95</td>
<td>24</td>
</tr>
<tr>
<td>Boden</td>
<td>27913</td>
<td>4285.10</td>
<td>184</td>
<td>66</td>
<td>17</td>
</tr>
<tr>
<td>Gällivare</td>
<td>18123</td>
<td>16818.24</td>
<td>720</td>
<td>259</td>
<td>65</td>
</tr>
<tr>
<td>Haparanda</td>
<td>9831</td>
<td>1866.62</td>
<td>80</td>
<td>29</td>
<td>7</td>
</tr>
<tr>
<td>Jokkmokk</td>
<td>5072</td>
<td>19334.40</td>
<td>827</td>
<td>298</td>
<td>75</td>
</tr>
<tr>
<td>Kalix</td>
<td>16248</td>
<td>3710.85</td>
<td>159</td>
<td>58</td>
<td>15</td>
</tr>
<tr>
<td>Kiruna</td>
<td>23178</td>
<td>20551.45</td>
<td>879</td>
<td>317</td>
<td>80</td>
</tr>
<tr>
<td>Luleå</td>
<td>76088</td>
<td>4962.19</td>
<td>213</td>
<td>77</td>
<td>20</td>
</tr>
<tr>
<td>Pajala</td>
<td>6193</td>
<td>8050.71</td>
<td>345</td>
<td>124</td>
<td>31</td>
</tr>
<tr>
<td>Piteå</td>
<td>41548</td>
<td>4678.23</td>
<td>200</td>
<td>73</td>
<td>19</td>
</tr>
<tr>
<td>Ålvsbyn</td>
<td>8183</td>
<td>1795.24</td>
<td>77</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>Överkalix</td>
<td>3395</td>
<td>2919.47</td>
<td>125</td>
<td>45</td>
<td>11</td>
</tr>
<tr>
<td>Övertorneå</td>
<td>4603</td>
<td>2492.52</td>
<td>107</td>
<td>38</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>249733</td>
<td>112085.48</td>
<td>4799</td>
<td>1731</td>
<td>537</td>
</tr>
</tbody>
</table>
This situation outlined so far is far from satisfactory. In order to change the underlying business cases it appears that a technical break-through is needed that enables a radically more cost-efficient infrastructure that is capable of delivering mobile broadband to large coverage areas.

A technical solution would require a new network architecture and new technology. One scenario is based on a nation-wide radio coverage with extreme large cells as suggested in [7], see Figure 3. Already in 2012 a suitable architecture was proposed internally in Ericsson. Here, few large transmission towers provided a backhaul network, while a large number of macro cells connecting in these super-cells, provided the coverage to the handheld. This network alone cannot provide the rural broadband coverage we target as the uplink connection (from the handheld to the super-cell base station) is likely to require too much power. Therefore, a large number of other macro cells provide the actual connection with the mobiles.

![Super-cell architecture in [7]](image)

**Figure 3**: Super-cell architecture in [7] constituting supercells and solar-powered macro-cells.

![Coverage of the Swedish TV network](image)

**Figure 4**: Illustration of the coverage of the Swedish TV network. The dark circles indicate the coverage area of three out of 40 TV channels in the UHF band (channel 21, 22 an 23, left to right, respectively). Could such large cells be used as a backhaul network for rural broadband coverage, and how would the small-scale radio-nodes operate without an electricity grid?
To put this in perspective, on a large scale, the TV network in Sweden today consists of roughly 50 high-power transmitters in high towers (see figure), each with large cell radii (order of 100 km). Equipped with new 5G technologies (beamforming, massive MIMO, etc., which we will return to later) and exploiting the abundance of spectrum available in the rural regions, decent fixed-wireless access could be provided everywhere. Figure 4 illustrates the coverage areas of a few of Sweden's TV towers [6].

While, the large super-cell nodes could be located at the large TV towers where access to the electricity grid is not a problem, a key question is how to power the macro cells in locations where electricity is not readily available. Therefore, provided that the backhaul network essentially covers the full surface, the critical energy questions relate to the deployment of the macro base stations. The macro cells need electricity for two essential functions: On one hand to provide the communication link with the user, and on the other hand to provide the backhaul communication link with the supercell base station. Both transmissions add to the energy budget of the node.

1.6 The energy budget of a base station as a critical factor

The remainder of this report focuses on one part of the above architecture vision: the cost-efficient powering of the rural macro-nodes. In particular we will explore the possibility of future macro base stations powered by solar energy in a local, on-site, micro-grid, such that an expensive connection to a main electricity grid is not needed.

Two aspects are relevant here: The energy consumption of the macro base station and the energy production based on local solar PV technology. While Chapter 2 addresses the former aspect, Chapter 3 addresses the latter.

![Figure 5: When will the reducing demand for energy meet the increasing capability to harvest and store energy and result in a cost-efficient and commercially-viable macro base station?](image)

Related to the energy consumption, today’s base station infrastructure is extremely inefficient as it typically spreads radiated power into a huge area, as well as consumes power that is there to give the base stations high capacity (for urban use cases). This further adds the issue of cooling and power supplies with restricted efficiency that have to be dimensioned for maximum capacity load situations. Not only does this design constraint affect power consumption, it typically also affects the price of equipment. This quickly becomes a design paradigm that is not in favour of cost efficient rural coverage. In Chapter 2 we explore the trends and a range of technical options that improve the ratio between usefully radiated power (coverage for a specific user at a specific place) and consumed power.
Related to the energy production, there is an ongoing evolution in solar power and battery technology that works favourably in a future vision of a mobile broadband infrastructure that have radically different characteristics in terms of cost and coverage. In Chapter 3 we explore the possibilities and limitations to use solar power for the local energy production of a macro base station.

Figure 5 illustrates the motivating idea behind the study in this report: While energy consumption of a macro base station will reduce over time and the cost/efficiency of solar energy harvesting and storage will increase there will be a time instant where the deployment of solar-powered macro base stations will be economically feasible. While this time instant has not yet come, this report shows on one hand that it is not far in the future, and on the other hand it identifies technology enablers that can speed up the two processes.

In summary, one of the main cost drivers is the need for electricity to power the network equipment. In rural regions where the electricity grid does not naturally reach all locations this cost driver is more pronounced than in other regions. In this report we present an initial assessment of the possibilities and challenges with powering radio nodes in extreme rural regions with solar power, a topic recently addressed in [8][9].
2 ENERGY CONSUMPTION OF BASE STATIONS

2.1 Today's base stations energy budget

In recent years a substantial number of research papers have been published related to the energy consumption of radio access networks. Much of this research was motivated by the strong need to reduce the carbon footprint of the network in the ongoing efforts to reduce the effects on the climate and its changes. Other, arguably stronger motivations were found in the operators' needs to reduce their increasing electricity bills.

While in this study the motivation is another (we target low energy consumption just in order to make rural deployments possible and feasible) our goal is the same: reduce the energy consumption of a base station.

The energy consumption of a macro base station has been shown in many studies to be composed of two independent contributions. Figure 6 (from [10]) shows the power dissipated by a macro base station during one week of service. A first contribution is independent of the traffic load at any time. It consists of the energy that is needed to simply keep the base station powered and in a stand-by mode, ready to accept any traffic and serve any users that may show up in its cell. Until very recently, this component amounted to roughly 1 kW of continuous power dissipation. A second component than solely depends on the actual traffic load at any given time. This part of the energy consumption is variable in time and adds another 0-500 W to the above figure.

A second observation made by many studies in the literature is the remarkable inefficiency of a base station. Figure 7 (from [11]) illustrates the energy consumption in the various parts of the base station. It reveals that, typically, just 4% of the energy consumed from the grid is radiated at the antennas for the benefit of the downlink communications.

Finally, Figure 8 (also from [11]) shows a widely accepted model for the energy consumption of a base station where the two components described above are distinctly visible and where, moreover, the variable traffic-dependent component is proportional to the amount of data transmitted in the downlink.
In the following we will discuss two enabling technologies that each address one of the two types of energy consumption components and hold a promise to drastically reduce these two.

Finally, an observation made by researchers at Alcatel is very relevant for the ideas in this report [12]. Figure 9 (from [12]) shows how the power of macro base stations is believed to reduce in the coming years. The projection was made in 2011 but there is no reason to believe why the trend would be significantly different based on today's knowledge. In essence the average power is projected to be about 300 W by 2020, but noticeable is the grey curve at the bottom of the graph showing the "idle system". This curve is particularly relevant in our study as the rural macro base station we envisage will mainly operate in a state close to what is recognized to be "idle mode". In rural regions traffic load is assumed to be low. The idle-mode power curve shows that by 2016 the power consumption is close to 100 W.
2.2 Potential and limits to reduce energy consumption

A macrocell in the new architecture provides two radio links (backhaul radio link with the supercell, and a classical radio connection with mobile users), both of which contribute to the station's energy consumption, along with other components of the station. Two key emerging technology shifts carry the promise for full areal coverage and cost-efficient deployment or cellular networks in rural regions. While this is not fully recognized by the community—the technologies are independently emerging by other driving forces than the rural markets—in our vision they come with potentially huge impact on future rural networks.

1. Large beamforming antenna arrays has the potential to reduce the efficiency of the traffic-dependent part of the energy consumption.

2. Ultra-lean system design and Sleep modes has the potential to dramatically reduce the idle-mode energy consumption of a base station.

2.3 Massive MIMO for energy reduction

First, the emerging technology of massive antenna arrays allows the deployment of base stations covering ultra-large cell sizes (over 50 km). It is widely acknowledged in academia and industry that deployment of very large antenna arrays at the base station side will form a key component of the 5G radio standards that very recently have started to be addressed by 3GPP. Technologies in academia referred to as massive MIMO are in the heart of the urban, capacity-driven 5G use cases and scenarios.

Recognized by few, the energy-efficiency of these very large antenna arrays also keeps a promise for the noise-limited, low-load rural and remote coverage scenarios. The large arrays can accomplish a beamforming gain that hugely exceeds today's and that beneficially affect the link budgets of large-cell macrocells. The pencil-sharp radiobeams produced by these base stations allow for increase of the cell radius without compromising implementation complexity, cost-efficiency or energy consumption.

Notably, very recently Facebook has launched a project—ARIES—based on these MIMO-beamforming technologies and with the aim to address rurality [13]. It is likely that the use of high
towers (such as TV infrastructure with its available high-quality backhaul and the available power) will play an important role.

2.4 Radio network redundancy and base station sleep-modes

Secondly, it is recognized that 4G base stations consume a relatively high percentage of their energy consumption independent of the actual traffic load. Until recently, a macro base station dissipated up to 1 kW continuously, just to keep it powered and to allow users to access its services – even in the absence of any users. The reason for this is found in the continuous transmission of broadcast and synchronization channels, along with pilot signals that jointly allow mobile stations to find, synchronize and access the network (see Figure 10).

This inefficiency is currently being addressed mainly for reasons of reduction of the aggregate radio network energy consumption. Operators worldwide are interested in reducing their carbon footprint and arguably more importantly, to reduce their electricity bills. As a result, new ultra-lean radio-protocols are being developed that are more user-centric, with the explicit goal to reduce the transmission overhead of the radio nodes and improve their energy efficiencies [14].

Again, this trend keeps a hopeful promise for the rural regions not covered by radio networks today. New future base stations building on these new ultra-lean radio-protocols allow design of macrocell base stations that continuously dissipate less than 100 W, which in turn will open up new possibilities for energy harvesting and renewable energy sources to power these base stations. The CAPEX reducing effect of this trend will be so large (no need for electricity-grid connections) that deployment in remote places will be economically affordable and these regions can be served under a regular market regime.

Figure 10: LTE downlink frame structure (from http://www.sharetechnote.com/html/FrameStructure_DL.html)
3 POWER SUPPLY: AVAILABILITY AND POTENTIAL OF SOLAR POWER

3.1 Today's coverage of the electricity grid in rural Sweden

The electricity grid in Sweden is a regulated monopoly. The grid owner has a concession to build the grid, where the electricity law distinguishes between two types of concessions: areal concession (“områdeskonsession”) and line concessions (“linjekonsession”). The former one gives the grid owner the right (almost a monopoly, see below for the exception) to build an electricity grid within a specific area. But the concession also includes the obligation to connect any network user (producer or consumer) that wants to connect. The other type of connection gives the holder of the concession the right to build a link (line or cable) between two locations following a certain path. Such a concession would allow somebody other than the areal concession holder to build an electricity link on the area.

The combination of all line concessions is referred to as the transmission grid (“stamnätet”) at 220 kV and 400 kV and as the regional grid (“regionnätet”) at lower voltage levels. The electricity grid owned by the areal concession holder is referred to as the local grid (“lokalnätet”). The line concession holder is also, after permission from the area concession holder, allowed to connect a new customer. This is the case for large industrial customers, large production units and increasingly for wind power.

For radio base stations, the power consumption is relatively small, so that the connection will be taken care of by the areal concession holder, i.e. the radio base stations are connected to the local grid.

The whole of Sweden is covered by areal concession holders. This implies that for every location in the country there is exactly one areal concession holder that has the obligation to connect a new customer if that customer demands so. Most of the remote parts of Northern and central Sweden are supplied by Vattenfall; for the remote parts of Southern Sweden E.On (previous Sydkraft) is the areal concession holder.

The areal concession holder has to charge the new customer for the actual costs of the new connection. These costs are higher for more remote locations. A template exists for customers with fuse size up to 25 A (5.7 kW single phase; 17 kW three-phase) and for distances up to 1800 m from an existing grid [16]. No template exists for distances exceeding 1800 m, so that remote locations are not covered. The table below gives the connection fee according to Vattenfall Eldistribution.
Table 2: Connection fee for short distance connections up to 25 A.

<table>
<thead>
<tr>
<th>Distance</th>
<th>Connection fee</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 199 meter</td>
<td>27 625 Skr</td>
</tr>
<tr>
<td>200 to 599 meter</td>
<td>27 625 Skr + 236.25 Skr/m</td>
</tr>
<tr>
<td>600 to 1199 meter</td>
<td>122 125 Skr + 140.00 Skr/m</td>
</tr>
<tr>
<td>1200 to 1800 meter</td>
<td>206 125 Skr + 208.75 Skr/m</td>
</tr>
</tbody>
</table>

The areal concession holder may also decide to postpone the connection to a later date to accommodate for the time it takes to extend the local network. Such delays may be especially big for large customers or wind parks where a strengthening of the regional network is needed. Strengthening of the regional network takes longer time because a separate concession is needed for every new link. In the local network, no such new concession is needed, but a new customer at a very remote location may still require one or two years to connect.

The most remote parts of Sweden are partly protected as nature reserves, so that building of cables and especially overhead lines may not be allowed or only after special permission has been obtained. This may cause further delay and costs for connecting a radio base station at a remote location.

A 100%-local energy supply, without any connection to the grid, would make that the costs and delay with connection to the electricity grid are not needed. A partly local energy supply, to cope with peak consumption, could make the connection cheaper. But there are no general rules to be given on how much cheaper as that will strongly depend on the local grid.

All customers connected to the local network of the same concession holder, have the same use of system tariff, independent of where in the local grid the customer is connected. Thus a radio base station in the centre of a city pays the same as a radio base station in the remote countryside, assuming they are in the same areal concession. Also the electricity price is independent of location (there are four different price areas in Sweden making electricity price in general lower in the North than in the South; but in one price area, the electricity price is the same for each location). The operation of the radio base station is thus independent of location; no matter if it is located in the centre of a city or in the remote countryside.

The network tariff consists of three parts:
- A fixed part per month;
- A cost per kWh consumed;
- A cost proportional to the highest kWh/h during each month.

The fixed part depends on the “subscribed power” also known as “fuse size”. The fixed part for small customers connected to Vattenfall’s distribution network in the north of Sweden, is shown in Table 3. For the costs per kWh the customer can choose between 20 öre/kWh throughout the year or a differentiated tariff of 59 öre/kWh during peak hours versus 16 öre/kWh off-peak.

Table 3: Fixed part of the network tariff for Vattenfall’s small customers.

<table>
<thead>
<tr>
<th>Fuse size</th>
<th>Costs per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 A</td>
<td>4 330 kr</td>
</tr>
<tr>
<td>20 A</td>
<td>6 170 kr</td>
</tr>
<tr>
<td>25 A</td>
<td>7 690 kr</td>
</tr>
<tr>
<td>35 A</td>
<td>10 800 kr</td>
</tr>
<tr>
<td>50 A</td>
<td>15 600 kr</td>
</tr>
<tr>
<td>63 A</td>
<td>21 100 kr</td>
</tr>
</tbody>
</table>

Getting part of the energy for the radio base station from a local source, like solar power, will mainly reduce the kWh part. However when solar power is combined with storage and the appropriate control system, it becomes possible to reduce the monthly peak consumption and the subscribed power. In [17] production of a solar power installation and domestic household consumption in Northern Sweden along with means to control peak loading were studied. There is even a possibility, under the
electricity law, for the owner of a small production unit, to get a small payment from the local network and to sell surplus energy to an electricity retailer.

With 100% local energy supply, the costs for using the electricity network are obviously zero.

Another reason for local energy supply is the reliability of the local distribution grid at remote locations. Table 4 compares the reliability for customers connected to four different distribution networks, all in Northern Sweden:

- Luleå Energi Elnät, an almost exclusively urban distribution network
- Vattenfall Eldistribution, an almost exclusively rural distribution network
- Umeå Energi Elnät, an almost exclusively urban distribution network
- Skellefteå Kraft Elnät, a mixture of rural and urban distribution networks

All data covers 2014 and was obtained from the Energy Markets Inspectorate (the energy regulator for Sweden). Data includes interruptions originating in the network operator by the local operator, but also interruptions originating elsewhere; it gives the reliability as the customer is exposed to, independent of which company is responsible for the interruption.

SAIFI gives the number of long interruptions (longer than three minutes) per customer per year; SAIDI gives the unavailability of the supply (in minutes per customer per year); MAIFIE gives the number of short interruption events (three minutes or less) per customer per year, where multiple short interruptions within a short period of time are considered as one event; CEMI 4 gives the percentage of customers that experienced 4 or more long interruptions per year; CEMI 12 gives the percentage of customers that experienced 12 or more long interruptions per year; CEMI 20 gives the percentage of customers that experience 20 or more long interruptions per year.

<table>
<thead>
<tr>
<th>2014 data</th>
<th>Luleå</th>
<th>Vattenfall</th>
<th>Umeå</th>
<th>Skellefteå</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAIFI</strong></td>
<td>0,61</td>
<td>5,64</td>
<td>1,54</td>
<td>2,68</td>
</tr>
<tr>
<td><strong>Less than 12 hours SAIDI</strong></td>
<td>46,31</td>
<td>335,76</td>
<td>47,17</td>
<td>143,98</td>
</tr>
<tr>
<td><strong>More than 12 hours SAIDI</strong></td>
<td>2,01</td>
<td>34,93</td>
<td>1,10</td>
<td>4,17</td>
</tr>
<tr>
<td><strong>MAIFIE</strong></td>
<td>0,61</td>
<td>5,84</td>
<td>0,86</td>
<td>2,61</td>
</tr>
<tr>
<td><strong>Number of delivery points</strong></td>
<td>40115</td>
<td>114093</td>
<td>58286</td>
<td>63861</td>
</tr>
<tr>
<td><strong>Number of delivery points without interruptions</strong></td>
<td>24457</td>
<td>13057</td>
<td>2747</td>
<td>11694</td>
</tr>
<tr>
<td><strong>CEMI 4</strong></td>
<td>7,4%</td>
<td>52,5%</td>
<td>7,1%</td>
<td>31,8%</td>
</tr>
<tr>
<td><strong>CEMI 12</strong></td>
<td>0,3%</td>
<td>17,7%</td>
<td>0,0%</td>
<td>4,9%</td>
</tr>
<tr>
<td><strong>CEMI 20</strong></td>
<td>0,1%</td>
<td>4,9%</td>
<td>0,0%</td>
<td>0,9%</td>
</tr>
<tr>
<td><strong>Number of customers with one or more interruptions longer than 12 hours</strong></td>
<td>0</td>
<td>424</td>
<td>13</td>
<td>75</td>
</tr>
</tbody>
</table>

### 3.2 Characteristics and requirements of micro-grid for radio nodes

A microgrid is a discrete energy system consisting of distributed energy sources (including demand management, storage, and generation) and loads capable of operating in parallel with, or independently from, the main power grid. The primary purpose is to ensure local, reliable, and affordable energy security for urban and rural communities, while also providing solutions for commercial, industrial, and federal government consumers. Benefits that extend to utilities and the community at large include lowering greenhouse gas (GHG) emissions and lowering stress on the transmission and distribution system).

Note that this is the “European definition” of microgrid. The United States’ Department of Energy gives the following description: “A microgrid is a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously”. Being able to operate in

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1 http://www.generalmicrogrids.com/#!about-microgrids/c1r3e
island is essential in this definition of microgrid, but in Europe the term is also used when the installation is not able to operate in island.

Different types of microgrids are to be considered here:

- Always in island operation; there is no connection to the public grid at all. This is how many remote locations are powered; but also for example many parking meters even in cities. The reason for the latter is that the network tariff would be a too high cost. The country of India is concentrating on this for the electrification of remote areas.
- Sometimes in island operation, sometimes connected to the public grid. Emergency back-up supply is an example of this, but the term microgrid is typically reserved for installations powered by renewable sources like sun and wind, although most emergency back-up installations are powered by diesel of gas.
- Always grid-connected. One of the first modern microgrids was such an installation in Japan where the rating of the grid connection was only about 10% of the peak consumption.

3.3 Solar power supply in rural Sweden

For the energy reaching a solar panel it does not matter much where the panel is located, although city locations may have somewhat less irradiation due to air pollution. But overall, we can use measurements from any location within the same climate zone to get an impression of the availability of solar power.

In Figure 12 some production figures for a 2.5 kW PV installation at the roof of the Per Högström laboratory with Luleå University of Technology in Skellefteå are shown. Skellefteå is located at the latitude of 64.8°N. This site consists of 18.5 m² panels fixed at 50 degrees tilt and 0 degrees south. The upper graph shows the daily energy production in kWh/day. The average production per day during the year is 8 kWh/day but it is clearly noticeable that the daily average energy production drops to 0.73 kWh/day (more than 10 times) during the period from November to January. The lowest and highest power production per day is shown in the lower graph of Figure 12. The peak power for this installation is about 2.9 kW.

Figure 13 shows a picture of the PV panels on 15th of March 2015 (top) and on 19th of January 2016 (bottom). Both days the sun was shining but the production in 15th of March was almost 14 kWh while 19th of January it was 0 kWh.

The blocking of the sun by foreground objects or by snow is though a problem in artic climate. SMHI produce solar irradence data for the whole country with the support from the Swedish Radiation Protection Authority and the Swedish Environmental Agency. This data is accessible through the STRÅNG database [18]. In Figure 14 below the daily energy production of the PV panels (red) is plotted together with the data from the STRÅNG data base.

The snow coverage could be handled with placing the panels vertically. In Figure 15 below is the monthly solar energy production per installed peak power (kWh/kWp) compared at 2 different sites, Östersund (blue) where the panels are roof-mounted and Uppsala (green) where the panels are vertically placed at wall of a building [19]. Also simulated values taking into account the angle for each site, Uppsala (purple) and Östersund (red), is shown. When comparing the two installations it is obvious that the energy production at the vertically mounted system is more spread out over the year. The measurement showed that annual energy production was about 20% lower with the panels vertically mounted.
Figure 12: Power and energy performance of a 2.5 kW PV installation in Skellefteå during the period from Feb. 15th 2015 to Feb. 15th 2016. The upper graph shows the daily energy production, the middle graph shows RMS current and lower graph is showing the power production (Note that the negative values is indicating that the power is going from the PV inverter to the grid).

Figure 13: Photo of the PV panels at 15th of March 2015 (top) and 19th of January 2016 (bottom)
Figure 14: Daily energy production from the PV panels (red) and Global Irradiation for the same location.

Figure 15: Monthly solar energy production per installed peak power during one year at two different sites Uppsala (vertically mounted, green) and Östersund (roof mounted, blue).
3.4 Energy storage requirements and relevant battery options

Table 5 shows an overview of existing storage options. Note that it exist other options as well and new technology is developing.

<table>
<thead>
<tr>
<th>Battery</th>
<th>Efficiency</th>
<th>Cycles</th>
<th>Wh/kg</th>
<th>Density (kWh/m³)</th>
<th>USD/kWh ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>50-95%</td>
<td>500</td>
<td>33–42</td>
<td>60–110</td>
<td>56–143</td>
</tr>
<tr>
<td>NiMH</td>
<td>65%</td>
<td>500</td>
<td>100</td>
<td>140–300</td>
<td>293</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>95%</td>
<td>500–1000</td>
<td>100–265</td>
<td>500</td>
<td>350</td>
</tr>
<tr>
<td>NiFe</td>
<td>65–80</td>
<td>5000</td>
<td>19–25</td>
<td>125</td>
<td>176–235</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>20-40%</td>
<td>5000</td>
<td>40000</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>25-40%</td>
<td>13000</td>
<td>10000</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

The difference of irradiance between different sites in the north of Sweden is not so large. Below in Figure 14 a comparison between the three different sites is done with data from “Strong”. The annual average difference is about 10% lower in Nikkaluokta compared with Skellefteå and Malmö is about 18% higher during the specified time period. The gap in solar energy in Nikkaluokta (November to January) compared with Skellefteå is however slightly longer which would indicate that even a larger energy storage is needed to cover the period. The energy storage requirement is basically proportional with the maximum length of the period without solar irradiation.

Assuming that the power consumption needed by the micro base station, shown in Figure 6, can be lowered by 80 % down to 200 W continuous power consumption it would require about 4.8 kWh per day on an average. Note that this is also assuming base station need continuous power but however is the expected traffic much lower at this type of site compared to data given in Figure 6. Given this and
regarding the production of the PV panels in Skellefteå (which produce about 8 kWh/day on average) this would indicate that there is a need for a battery power during approximately 3 months (blue line indicated in Figure 14 above). During these circumstances this would indicate that a battery capacity of 432 kWh or roughly 5 to 6 Tesla car batteries is needed to cover this period.

Comparing this example with Table 5 above about 1 m$^3$ of Li-Ion battery is needed to a cost of 175 000 $ or a 5 m$^3$ lead-acid battery at a cost of 50 000 $.

### 3.5 Trends of batteries and PV panels

The cost of both batteries and PV panels is reported decreasing. The development in battery technology is on-going and one driving factor is the EV-industry. Lead-Acid batteries are one of the oldest rechargeable battery types. It can provide a high surge current and is relatively cheap but the energy density is low. Among other battery technologies Li-Ion has today the largest market. The cost of Li-Ion batteries has from 2000 to 2012 dropped about 70 %. The Division on Engineering and Physical Sciences and Transportation Research Board of the National Research Council, US, is estimating 50 % lower battery price within ten years [20].

![Figure 17: Estimated Li-Ion battery cost.](image)

Solar energy has been relatively rare electrical energy source but has gained in popularity during the last decade and the installed capacity between 2004 and 2014 increased by more than 20 times in Sweden. One of the driving factors is that the price of PV installations has decreased considerably. According to the Swedish Energy Agency it is estimated that the average price of PV panels has during the period from 2004 to 2014 has dropped from 70 to 8.15 Skr/Wp and the average system price during 2014, range from 13 to 15 Skr/Wp depending upon size, etc. [21].

### 3.6 Wind power as an additional energy source

Wind power also suffers from large variations in production and overall wind power is seen as less reliable because of the daily variations. However the long arctic winter makes that a two or three month period with close to zero supply from solar power should be expected. Wind power also shown an annual cycle, but its minimum is during the summer months. Figure 18 shows the daily production for a 1.7 kW wind turbine located somewhere in the middle of Sweden. The data as obtained as measurements from an 850 kW turbine at that location and scaled down by a factor of 500 to obtain an average daily production of 8 kWh/day, the same as for the solar power installation in the previous section. No data for northern Sweden was readily available, but the general patterns are expected to be the same. We see that the production can be low for several days in a row, but the periods with low winds are still short compared to the two to three months periods for solar power.
Figure 18: Daily energy production for an 8.5 kW wind turbine during three consecutive years,
4 FURTHER WORK – OPEN RESEARCH QUESTIONS

4.1 Opportunities and technical possibilities

Based on the results in Chapters 2 and 3 we now phrase the desired and feasible target of a 100 W macro base station. On one hand, results in Chapter 2 suggest that this target is within reach technology-wise. Exploiting the approaches by ultra-lean design and massive array beamforming, this target is highly feasible. Based on the results in Chapter 3 powering such a base station in rural Northern Sweden would require about 7 m$^2$ of PV panels, along with either 0.5 m$^3$ of Li-Ion batteries or 2.5 m$^3$ Lead-Acid batteries. While such battery requirements today are probably prohibitively expensive, in a near future battery cost may drop to levels that allow cost-efficient installation. Moreover, exploitation of other energy resources such as wind power could significantly reduce the need for batteries.

4.2 Challenges and relevant research questions

In this section we list a number of concrete research questions that emerge as a results of this study.

- Network dimensioning under tight energy-constraints per node. This is a research area that has been explored for wireless sensor network, but has not been approached for the cellular networks. A key aspect here is to build in the communications system models a probability that a network node is unavailable (for lack of energy that powers it). Such models will lead to different optimal network topologies and architecture choices (including device-to-device) compared with today's paradigm where nodes are a priori assumed to be always on. The idea of redundant networking is likely to find a place here.
- How much does massive MIMO technology reduce the energy consumption of a macro cell? This issue also combines with using optimal frequency bands for achieving rural coverage.
- How is the initial search of users in a cell carried out efficiently (low energy consumption) in a massive MIMO-based macro-cell? Including the issue of waking sleeping macro-cells up when needed.
- How much of the energy-demanding downlink signalling by the base station (broadcast channel synchronization channel, pilot signals) can be discarded as a result of the low-capacity (small number of users in a cell) assumption?
- Dimensioning of battery storage when using a combination of solar power and wind power. This includes finding the optimal tilt angle and direction for our specific application. Most earlier work was towards maximizing the annual energy production. For our application, the production during winter is much more important and cannot be compensated by higher production during summer.
- Alternative solutions for connecting to the grid of low-power installations at extremely rural locations. Methods for using solar power and battery storage in combination with an unreliable grid to obtain a reliable supply to a remote radio base station.
- Performance of battery and energy storage during low temperatures.
- How to design a cost-efficient wind generator, that can operate in harsh winter conditions.
REFERENCES


