Solar vs Diesel: Where to draw the line for cell towers?

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ABSTRACT

Cellular networks in developing regions continue to rely heavily on diesel for energy to provide network coverage due to the paucity of reliable grid power which directly impacts the network's economic viability and long-term sustainability. At the other extreme, solar powered cellular installations have gained prominence but have faced their own adoption challenges including inability to provide adequate and reliable 24x7 power supply, need for large land footprints and lack of efficient power storage. In this paper, we perform a detailed economic cost analysis comparing diesel powered cellular networks with solar powered cellular networks. The key goal of this paper is to establish the cross-over boundary beyond which solar powered installations are better than diesel powered alternatives. We perform a detailed analysis based on actual diesel consumption data from a large telecom operator in a developing region. Using our model, we can also easily perform an extended analysis based on future projections on solar efficiencies and future cellular network designs.

Categories and Subject Descriptors

C.4 [**Performance of Systems**]: Modeling techniques

Keywords

Solar, Diesel, Cellular Networks, Economic Modelling

1. INTRODUCTION

The current cellular infrastructure in developing regions has heavy dependence on diesel-powered generators which leads to sustainability and affordability issues for rural populations. For example, in India the grid power is unreliable both in urban and rural areas, forcing a majority of Indian operators to rely on backup diesel power generators thereby making telecommunications the second largest consumer of oil in India [36]. This increases the operational cost and affects customers, so the cellular providers want to explore alternative green energy sources. While the current model is sustainable in urban settings, achieving sustainable access in rural areas is significantly harder due to several factors: low population densities, low purchasing power, lack of any reliable power source, lack of good back-haul connectivity (fiber or telephony lines) [13, 16].

At the other end of the spectrum, solar powered cell towers have gained prominence in several developing regions [25, 36]. Despite their promise as an alternative energy source, solar powered cell towers have not yet been adopted on a large scale due to several operational challenges. First, the traditional design of cell towers are inherently power hungry and require high power budgets which are not easy to meet using just solar powered installations [25]. The power efficiency of solar panels continues to be relatively low in terms of Watts/m^2 and one would need large land areas to power a conventional cell tower. Second, to achieve high reliability in solar-powered off-grid installations, one may need significant over-provisioning compared to the average power demand to handle fluctuations in sunlight availability and peak demand needs. Third, existing battery technologies for power storage are inefficient and archaic [38]; large solar installations typically store only a small fraction of the generated power.

In rural contexts, conventional cell towers rely on *big cells* which consume large amounts of power and aim to support several users. The big cell model is not appropriate for solar powered installations due to high power requirement. There has been a recent emergence of new community base station designs with ongoing pilot deployments [3, 10, 14]. The solar-powered wireless deployments are best suited for these *small cells* which support fewer users(use fewer channels) and is thus limited by the power levels that can be supported by solar panels. In this paper, we aim to understand the fun-

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damental economic tradeoffs between diesel-powered big cell model with the Solar-powered Small Cell (SSC) model. To this end, we propose a new economic modelling framework that provides a simple and effective way of comparing the cost structures of these two different cellular network designs. Using this framework, we determine the constraints under which the solar-powered model is significantly more cost-effective than diesel-powered model.

This paper makes the following contributions. First, using operational data obtained from surveying people from a large cellular provider, we demonstrate the magnitude of the power scarcity problem by cellular networks including: presence of massive power outages lasting 5-10 hrs/day, extensive diesel consumption by cellular networks to provide constant service and varying load on cell towers throughout the day. Second, we provide a generic economic framework that can be used to reason about solar vs diesel powered installations for cellular networks. Third, we perform a detailed comparison of the conventional diesel-powered *big cell* model with the emerging solar-powered *small cell* (SSC) model and argue for the effectiveness of the SSC model for future cellular network adoption, especially in rural areas. Finally, we show that ongoing technological and cost trends in cellular networks and solar energy seem to perfectly align with a much larger scale adoption of the SSC model leading to green cellular networks.

2. THE CONVENTIONAL BIG CELL

Two of the basic challenges faced by conventional cellular networks that are rolled out in rural areas are power and low demand. Cellular networks traditionally use the “big” cell coverage model for providing connectivity in rural areas. This typically comes at the expense of high power consumption. Unfortunately, grid power is largely unavailable in rural setting forcing rural cellular network providers to rely on diesel to meet the power demands which increases cost. Next, we outline the power and cost challenges in greater detail.

2.1 Power challenges

Cellular networks invest a reasonable fraction of network equipment costs in power equipment, especially for cleaning the power source. A single GSM base station could consume between $5 - 10$ kW in the urban areas with lower power levels [4]. They use low power in urban areas so that more users can be accommodated on same channel in neighbouring areas. A typical ex-urban cellular base station has higher power level, and can easily consume $10 - 20$ kW of power.

Alternative renewable power is essential for running rural wireless networks. Grid power, where available in rural areas, is unstable and intermittent; many villages in Sub-Saharan Africa experience a power outage for 6-12 hours every day [17]. A 220V power supply in India shows regular fluctuations from -1000V to +1000V, which triggered a device failure rate of $40 - 50\%$ in the Aravind wireless network in South India [32].

2.2 Low demand

Striking the right balance between demand and cost is critical to economic viability in rural regions. With low user density and low purchasing power, rural users clock little network bill-able time [27] to generate any significant revenue, thereby providing little incentive for providers to tap rural markets. Previous studies [3, 15] argue a strong correlation between cellular network coverage and the population density. This indicates that cellular coverage is primarily available in areas where population densities are quite high and connectivity in rural areas has remained significantly low. Figure 1 shows the strong correlation between population density and cellular coverage in Kenya.

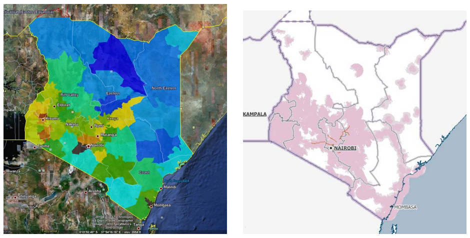

Figure 1: Strong correlation between population density (left, with red denoting most dense, and blue denoting least dense) and GSM cellular coverage (right) in Kenya.

Several governments have created a Universal Service Fund as a means of levying a tax on urban users for making rural connectivity viable; the things are still far from perfect because these programs are often too slow. The direct result is that millions of people are without telephony connectivity even today. The end result of the high costs is that calling rates are exorbitant relative to the purchasing power of users [26]. This is a deterrent to promoting mobile services in rural areas. To enhance demand and revenue, the only option for providers is to significantly lower usage costs, which is hard to achieve due to high capital and operational expenditures of rural cellular networks.

3. A CELLULAR ISP’S PERSPECTIVE

In this section, we outline the power problems and the diesel consumption characteristics of a large cellular ISP operating in a developing country with more than 30 million active subscribers. We obtained aggregate statistics about power outage, diesel usage and call load from the cellular ISP. We outline the key characteristics that we learn.

3.1 Power consumption

A regular cell tower site has 3-4 smaller cells that transmit and receive in different directions. A GSM cell tower covers area with radius of 35 Km but the actual coverage depends on a lot of other factors such as topology, soil type, antenna height and direction and the obstacles the signals have to break through. Cell tower sites are connected to the national grid for power and diesel generator or batteries to deal with grid failures. Each cell tower site offers about 300 to 400 E[1] of service in cities per day. The cell towers sometimes offers more than 400 E in ex-urban areas because of lack of choices

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[1] E stands for Erlang-unit of call load

Table 1: Aggregate Diesel consumption distribution for over one thousand sites, from March to December 2013.

Month and Year	Diesel Consumption
March 2013	314,809 litres
April 2013	328,002 litres
May 2013	343,115 litres
June 2013	301,075 litres
July 2013	211,587 litres
August 2013	163,467 litres
September 2013	126,570 litres
October 2013	96,800 litres
November 2013	98,205 litres
December 2013	81,572 litres

Table 2: The distribution of power outage across sites. x denotes the number of hours grid electricity was not available.

Grid Power not available (hrs)	Percentage of sites
$0 < x < 2$	11.2%
$2 \leq x < 5$	22.0%
$5 \leq x < 10$	48.0%
$x \geq 10$	18.8%

and more coverage by a single cell tower. The cell towers in cities run on lower transmission powers to allow re-usability of channels in neighbouring areas and thus support more users. The busiest hour of the day is around 8 pm for most of the cell tower sites and they have to cater for 30-40 E on average. Some of the cell towers have an intelligent shutdown feature enabled in modern sites where cells are turned to power saving mode automatically when there is no call running and they come back to full power instantly when there is a call request. A single cell can consume between 3KW and 6KW power for this cellular provider.

3.2 Grid power availability

The current infrastructure of grid power is neither enough for the high demand nor stable in developing countries. Many villages in Sub-Saharan Africa experience a power outage for 6-12 hours every day [17] and rural areas of Pakistan face power outages of 20 hours at some times of year [23]. Power outages in hot summer months can be 4 times more than winter months. Table 2 shows the fraction of sites experiencing different ranges of grid failure(hours) per day, averaged over a week. While a typical outage from $5-10$ hours is considered the norm for many cell towers (which is an exceedingly high number), there are occasions where grid power unavailability can last for roughly 20+ hours a day in the worst case as also noticed in other studies [23]. We can see that only 12.2% cell towers have grid power unavailability for less than 2 hours per day which is very surprising.

Table 3: Coarse statistics about number of calls received at a few different sites in different time intervals.

	Average	Maximum	Minimum
0900-1300	4244.4	11363	285.3
1300-1700	4906.1	12911	392.7
1700-2100	3694.2	9556.3	204.7
2100-0100	1301.7	3149.3	86
0100-0500	142.9	392	7.3
0500-0900	909.6	2310.3	34.7

We received information for sites that span the spectrum of urban and rural settings in the country. It could be seen that grid power availability becomes a larger problem, the farther we are from the city and even in urban contexts, a power loss of $5-10$ hours seems to appear as the norm. To provide further context it can be clearly witnessed that a significant number of towers experience over 10 hours of outage while the average hovers around 5 and 10 hours across all towers. These numbers are exceedingly high and directly indicate the need for alternative energy sources to run cell towers. In most developing regions, diesel powered generators seem to be the natural choice. In countries like India, diesel prices are subsidized due to their usage for commodity transportation and agriculture; this enhances the use-case for diesel over other oil sources.

3.3 Diesel Consumption

Table 1 shows how the aggregate amount of diesel consumed at over 1000 sites varies from March 2013 till December 2013. Table 1 shows that around 1000 sites can consume as much as $343,115$ litres of diesel in a single month. The amount of power needed by a base station site is directly dependent on the load it is dealing with. The power requirement of a particular cell tower varies during the day as there is variation of load at different times of the day. Similarly, the diesel consumption characteristics also vary highly between summer and winter. In urban areas, given the heavy usage of air conditioning in summers, the grid availability is much lower and hence the diesel consumption is correspondingly much higher. During winters, there is not a heavy usage of grid powered heating equipment and hence the stress on the grid is much lower; hence the grid availability is higher and diesel consumption is correspondingly lower.

We also observe that the power consumption from diesel is about a factor $10-20$ higher than the power requirements of the cell base stations. This large gap is due to the high inefficiency of diesel generators. Diesel generators can have an efficiency of lower than 15% and with poor maintenance, the efficiency could potentially be much lower. The power generated by a diesel generator also needs to be cleaned and stabilized before being fed to a cell tower base station. While there have been several technology enhancements that have been suggested for diesel generators, technology changes, such as engine modifications, exhaust gas recirculation, and catalytic after treatment, take longer to fully implement due to slow fleet turnover [22].

Diesel generators also leave a massive carbon footprint. According to the data, a single site can consume up to 90 litres of diesel in a day. The carbon dioxide emission per litre of diesel is 2.614 Kg [12]. This means that a site at average produced 235 Kg of carbon dioxide emission every day in the month of April. According to a policy report [35], 530 million gallons of diesel was used every month in India in 2010, producing 11.9 kilograms of carbon dioxide per gallon.

3.4 Load variations

A critical factor determining the power consumption of a cell tower is the call load. Table 3 shows the variation in the hourly load of a few different sites of the cellular operator. We make three observations. First, most cell towers achieve peak loads at similar times, thereby imposing a heavy load on the grid during specific time periods; this does correlate with grid unavailability during peak times leading to the ironic observation that grid power may be unavailable during most essential time periods. Second, given that demand can be very low at night, cell towers often follow the practice of completely switching off the base stations during night times leading to cell unavailability for extended periods at night (unless they have the intelligent shut-down option which not all cell towers have). Third, cell towers that observe relatively low demand but yet have non-zero demand have relatively high power consumption in dormant state (since the receiver is constantly on); this can be potentially reduced by intelligent radio management.

4. SOLAR-POWERED SMALL CELLS

A natural alternative to the conventional "big" cell model is the solar-powered small cell model; we refer to this connectivity model as Solar-powered Small Cells (SSC). The SSC model naturally follows as an amalgamation of ideas from the large body of work on rural wireless networks [3, 10, 14]. Given the limited power efficiency of solar panels, the power consumption of a completely solar powered wireless node in SSC is limited by the number of wireless channels; this directly constrains the number of supported users of a SSC cell, thereby resulting in a "small" capacity cell best suited for low population density areas. A SSC network is tailored for the typical scenario where rural populations are congregated over small villages which are geographically sparsely distributed around the city/town. The SSC design philosophy is to provide *focused network coverage* using "small" cells in these rural regions and interconnect these regions using back-haul networks. The specific SSC network structure we envision is a natural extension of existing works on rural wireless networks [3, 10, 14, 15]. A typical SSC network leverages OpenBTS-based low-power base stations to provide local coverage in a village and interconnects these base stations with long-distance wireless or wired back-haul links. For wireless back-haul connectivity, SSC can leverage potential options including microwave links, long-distance WiFi [29] or cellular back-hauls [20, 34]. Where a single OpenBTS base station is insufficient, we envision a multi-hop wireless mesh network to interconnect a few local OpenBTS installations.

To extend cellular connectivity to each region, SSC uses OpenBTS (Open Base Transceiver Station), a software-based GSM base station that operates over different radio hardware devices like USRP. It allows standard GSM-compatible phones to make calls and terminates calls on the same box, and forwards the voice data (VoIP) to the open-source PBX system via SIP. The advantages of using OpenBTS + Asterisk are: a) end-users can use their existing cellular phones, b) it can be made to inter-operate with existing telephony networks, c) it supports trunking to utilize bandwidth efficiently, d) it allows flexibility in the choice of voice codecs used in the back-haul, such that network capacity can be optimized, and e) the power required to run the entire setup is much less than traditional GSM base stations, though the coverage capacity is restricted to fewer users.

By restricting the coverage capacity, SSC significantly lowers the net power consumption. Given that the back-haul links do not consume too much energy, the net power consumption of a SSC node can be restricted to few hundred watts, which is about a factor of $50 - 100$ times lower than that of a cellular tower. Reducing the power consumption to such low levels is critical to enable a small solar panel system to reliably power each SSC node for prolonged periods. The real-estate requirements for the corresponding solar panels at a SSC node are also limited. Together, the focused coverage design combined with the use of SSC point-to-point back-haul links, OpenBTS cells and solar panels is critical to significantly reduce the cost of the SSC network.

4.1 Engineering for High Availability

Given the energy consumption profile of a cell tower, a key question is: how much solar power is required to provide a certain level of energy availability guarantee for the cell tower? To answer this question, we consider a practical setup where grid may be available for a certain amount of time during the day. We consider three specific distributions: Let $P()$,$K()$ and $H()$ refer to the energy distribution (based on load), the grid unavailability distribution and the distribution of sunlight availability across a day. We used the sunlight availability data from Munawar's work [31] and rest of the data from an operational cellular company. Based on the variation in outages and differences in load throughout the day, we calculate the power that solar panels need to produce in the sun hours to guarantee a certain level of availability. Given the actual outage time-periods may be unknown in advance, we can either plan for the average case or the worst case. For different power ratings and grid unavailability, we calculate the power that solar panel needs to produce per unit time for compensation of the missing energy. For example if the median grid power unavailability is denoted by $K(median)$ and it is distributed over average load $P(avg)$ while sun is available for average sunlight hours $H(avg)$, then we can find the power rating required from solar panels by using the simple formulation:

$$\frac{P(avg)K(median)}{H(avg)} \tag{1}$$

This provides the average case setting and is the minimum solar panel generation requirement to guarantee that the remaining battery power is sufficient to provide 100% availability assuming that the power requirement is average during off-grid periods and the outage time follows the median case. Planning for worst-case would entail a much higher solar panel requirement which may not be practically feasible. A pragmatic approach may be to design for average load but 95th percentile of the grid unavailability.

4.2 Power needed for reliability

Based on operational power consumption data, we aim to answer the question: how much solar energy is required to achieve a certain level of reliability under different call loads and grid unavailability settings? In this analysis, we do not consider solar panel or battery inefficiencies; the output power computed equates to the final clean power required for a certain level of availability. For this analysis, we use the distribution of call/data load and the unreliability of the grid power from the operational data gathered from the large cellular operator. We evaluate how different scenarios of load variations and grid unavailability changes the amount of power that solar panels need to produce to guarantee high availability service. Different base stations have different power requirements. Our results are calibrated based on the operational power specifications from a cellular provider where the maximum power requirement of the cellular base station ranges between 2 KW to 6 KW. In other words for this analysis, we calibrate the power requirement at a certain load level to be a fraction of the maximum load (assuming the idle power at zero load is a fixed fraction of the peak power). We show the results for different base stations that have a maximum power requirement between 2 KW and 6 KW in Figure 2. In Figure 2, $P(max), K(95)$ bar refers to the amount of power solar panels need to produce (for the number of hours that sunlight is available) to deal with maximum load and 95th percentile of grid failure(from our data of several sites). Similarly, $P(max), K(avg)$ shows the amount of power solar panels need to produce to deal with maximum load and average grid failures. $P(avg), K(avg)$ shows the amount of power solar panels need to produce to deal with average call load and average grid failures. We can see that the amount needed to deal with the particular scenario of $P(max), K(95)$ is significantly higher. The key take-away here is that, engineering for 100% availability at average load case is easily feasible while engineering for the worst case is significantly more expensive and represents an 80% higher solar energy specification requirement than the average case. We observe that to achieve high availability (95%), the clean solar output power should be a factor $2.2 - 2.5$ higher than the average power required. These results are expected to be same for big cell base stations that consume 20 KW or more because the trend stays the same.

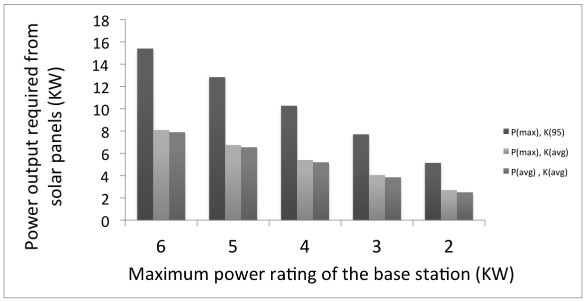

Figure 2: Power Requirement vs Solar output required for reliability

5. ECONOMIC ANALYSIS: SOLAR VS DIESEL

In this section, we aim to understand under what conditions is a Solar powered site model significantly better than the conventional diesel-powered rural cellular site. To analyze this question, we propose a simple and generic economic modelling framework for performing a cost-based analysis of three different cellular network designs from a pure energy standpoint: solar-powered network, diesel-powered cellular network and a grid-powered cellular network. Our goal is to establish the key energy considerations that drive decisions to power cellular base stations in rural areas. Our economic model has three distinctive features:

- We are interested in understanding how energy considerations for a base station will vary depending on how far it is situated from a city. This perspective is interesting because a number of parameters that are of interest to us, such as population, transportation, power availability and so on, can be modeled with respect to how far the region is located from a densely populated urban center. There is some precedent to this mode of discussion [9].
- We assume an amortized daily operational cost. Our model differs from Jhunjhunwala et al. [25] in how we incorporate distance from the city as a crucial metric that determines the operating regimes for the different energy sources under consideration.
- Our model is built to align with the overall objectives of a corporate cellular operator who is mandated with designing and implementing a cellular architecture catering to exurban and rural communities. In contrast to previous work [7, 25] that recommend a decision-theoretic framework to solve a constrained optimization problem where the objective function is the overall energy cost, we specify a novel randomized allocation scheme that assigns a probabilistic weight to the decision behind constructing a base station depending on the parameters of interest. This allows us to build an elegant and simple theoretical framework that we validate with real-world numerical evaluations.

We consider two alternate scenarios to the solar model: grid-based and diesel-based. In formulating our model, we make a simplifying assumption that a base station is powered entirely by one of these sources. We believe this provides better insights for a cellular service operator in terms of clearer feasibility regimes within which one alternative outweighs the other, as opposed to formulating and solving a constrained optimization problem that incorporates all three sources. For a rural population center that we will denote v, we will denote $r(v)$ as the distance from v to the closest urban center. Our model validates the following hypothesis: *there are three feasible operating regimes parameterized by* $r(v) < R_g$, $R_g \leq r(v) \leq R_g + R_d$, $r(v) > R_g + R_d$ *wherein grid, diesel and SSC are respectively most viable from a cost-consideration viewpoint.*

5.1 Notation and parameters

In our model, we compare the SSC architecture in the context of grid-powered and diesel-powered cellular architectures. We evaluate the cost structure in each model, and identify the scenarios in which each architecture is viable. As highlighted earlier, our discussion is structured in terms of geographic proximity of a rural center to a densely populated urban region that has access to a reliable power grid. As we

Table 4: Notation for main parameters in economic analysis

Notation	Definition
r	Distance from urban center
R	Average distance between two urban centers
R_g	Extent of grid coverage from urban center
$d_b(d_s)$	capacity of a big-cell (small-cell) base station

move away from the city, access to 24/7 industrial power supply becomes more limited, and other energy sources are in play. Table 4 gives notation for the different parameters that we will use. In addition to distance from an urban center (r), the geographical parameters include capacity(number of users supported) of a base station (d_b, d_s), and the average distance between two cities. The capacity of a base station is relevant to determine how many base stations are required, while the average distance between two cities gives the operating boundary within which to evaluate the different architectures.

5.2 Randomized allocation design of cell towers

With the goal of designing a cellular architecture mandated to cover exurban and rural population regions, we propose a simple randomized spatial allocation scheme that places a base station in a region distance r from a city with a probability density function $p(r)$. Such a density function has the following desirable properties:

- *Property 1:* The density function is proportional to the number of base stations necessary at distance r from the city and with capacity d, (r/d).
- *Property 2:* The density function is proportional to the population density at a point at distance r from the city, denoted $\eta(r)$.

It is not hard to motivate both of the above properties: the further away a population region is from the city, for a fixed capacity d, the number of cell towers needed will be larger[2]; and a base station should be built in a region in proportion to the population of the region. We set $\eta(r) = N_0 e^{-\alpha r}$ to be the population density function where N_0 is the conceptual central density (measured in number of persons/unit area) and α is the density gradient. This formulation is well-supported by several population studies [1]. Therefore, our allocation scheme builds a base station with probability density function $p(r)$ given by

$$p(r) \propto \frac{N_0 r e^{-\alpha r}}{d} = \frac{A N_0 r e^{-\alpha r}}{d} \tag{2}$$

where A is a normalization constant chosen appropriately to make $p(r)$ a probability density function.

5.3 Grid power

We first consider the existing power grid as an energy source. Our assumption here is that power from the grid is always available. Although this is not always realistic, we argue that unreliable power generation can suitably be supplemented with the help of backup generators, the cost of which can be outlayed within the daily operational costs accruing to grid-based power.

For simplicity, we will also include within the daily amortized cost, any fixed costs such as connecting the base station to the grid, and labor costs. Assuming a unit cost of c_g^0 and power requirement of P for a base station, the grid energy cost for powering a single base-station is:

$$c_g(r) = P c_g^0 \tag{3}$$

Note that in (3), $c_g(r)$ is independent of r. This makse sense since the region is covered by a pre-existing grid, and we have already subsumed the operational cost in laying down grid lines. Further, assuming that the grid only extends upto R_g distance from an urban area, for $r > R_g$, we can no longer consider the grid as a viable option. Finally, it is reasonable to assume that the population in exurban areas covered by the power grid will still be large enough to sustain building big-cell base stations. Using the pdf in (2), the total expected cost for grid-power is given by:

$$C_g = \frac{A P_b c_g^0}{d_b} \int_0^{R_g} N_0 r e^{-\alpha r} dr \tag{4}$$

5.4 Diesel-powered base station

As mentioned earlier, we assume that a diesel-powered base station would only be considered as a viable option if the village is off-grid. Let P_d^0 be the power provided by a unit volume of diesel. Assuming that diesel needs to be transported directly from the closest urban center, costs are given by $r c_t + V_d c_d^0$ where c_t is the transportation cost per unit distance[3], V_d is the volume of diesel required to power a typical daily load, and c_d^0 is the cost of the fuel itself per unit volume. Therefore, cost is:

$$c_d(r) = r c_t + V_d c_d^0 \tag{5}$$

Given the fixed transportation costs, diesel-generators are used to power big-cell base-stations. Therefore, the overall expected cost is:

$$C_d = \frac{A}{d_b} \int_{R_g}^{R} \left(r c_t + V_d c_d^0 \right) N_0 r e^{-\alpha r} dr \tag{6}$$

5.5 Solar powered small cells

The cost for a solar-powered base station is mainly driven by two variables: number of PV cells required for operation, and land area needed to house the solar cells. Let c_{pv} be the amortized daily operating cost for a solar installation at a base station, and A_{pv} the corresponding land area needed, with $c(r)$ be the daily rent per unit area of land. Then, the energy costs for solar can be framed as:

$$c_s(r) = A_{pv} c(r) + c_{pv} \tag{7}$$

We assume that $c(r)$ follows an exponential behavior, and this is supported by studies in land-rent theory [11]. Let c_r in (7) be given by $c_r = C_0 e^{-\beta r}$ where C_0 is denoted the central rent and β is the "rent gradient". As in 5.4, capacity

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[2] It can be shown by a geometric argument that the number of base stations is $\pi r / 2d$

[3] since transportation happens in bulk we will assume unit volume costs are immaterial

Table 5: Parameters

Notation	Value	Remarks
R	100km	see §5.7
R_g	10km	see §5.7
R_d	2km	see §5.7.1
d_b/d_s	10	$d_b \approx 10, d_s \approx 1$
P_b	20kW	Balshe [6]
c_g^0	155 Rs./kW	Jamil [19]
c_t	200 Rs./km	see §5.7
c_d^0	50 Rs.	see §5.7
c_{pv}^s	159 Rs./day	Panigrahi [28]
C_0	40	Dowall [11]
V_d	50 litres	Panigrahi[28]
α	0.19	Adhvaryu [1]
β	0.18	Dowall [11]
A_{pv}^s	13.5 sq.m	Panigrahi [28]

constraints limit solar-powered base stations to be small-cell. Super-scripting the necessary parameters A_{pv}^s, c_{pv}^s to denote a small-cell base station, the total expected cost of solar-powered base station is:

$$C_s = \frac{A}{d_s} \int \left(A_{pv}^s C_0 e^{-\beta r} + c_{pv}^s \right) N_0 r e^{-\alpha r} dr \qquad (8)$$

5.6 Crossover boundary for viability of SSC over diesel

In (5) and (7), we specified the respective cost formulations for setting up a base station using diesel and solar as energy sources. Both these expressions have an explicit dependence on the distance from an urban center; for solar, this is captured in the land rent which we assume to be non-increasing in r, and for diesel, it is the transportation cost of fuel which is non-decreasing in r. We now derive a closed form expression for a tipping point distance $r = R_g + R_d$ for which $c_s(r) < c_d(r)$ for all $r \geq R_g + R_d$. Substituting, canceling out common terms on both sides, and equating (5) to (7), we have:

$$\frac{A_{pv}^s C_0 e^{-\beta r} + c_{pv}^s}{d_s} = \frac{r c_t + V_d c_d^0}{d_b} \qquad (9)$$

Note that since the left-hand-side is continuous and monotonically decreasing while the right-hand-side is monotonically increasing, (9) will have a solution as long as

$$\frac{A_{pv}^s C_0 + c_{pv}^s}{d_s} \geq \frac{V_d c_d^0}{d_b} \qquad (10)$$

If (10) is not satisfied, then $c_s(r) < c_d(r)$ for all $r > R_g$ and demonstrates that for the given parameters, diesel power is not viable under any circumstance.

5.7 Empirical Evaluation

To empirically evaluate and compare the SSC model with diesel, we estimate realistic values for all the parameters in our model based on current market prices (for solar, grid and diesel) and models from related work where appropriate. Table 5 summarizes these parameters along with appropriate references to related work that drove the specific choice of values for individual parameters. Based on average distance between two cities in India with population 1 million

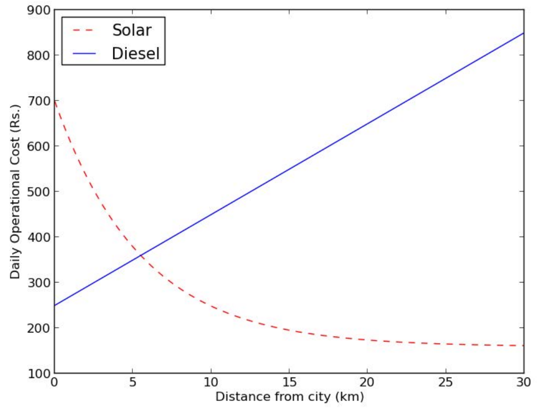

Figure 3: SSC cost vs. diesel

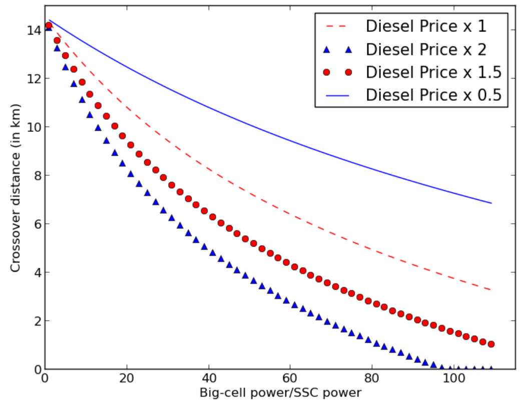

Figure 4: Crossover distance as a function of power ratio.

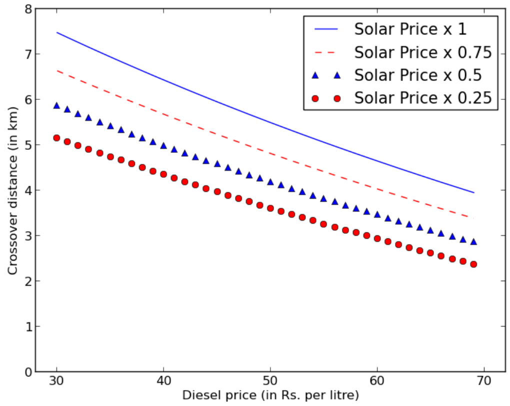

Figure 5: Crossover distance as a function of diesel price

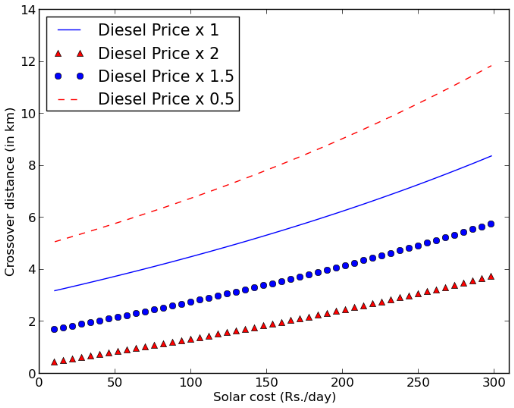

Figure 6: Crossover distance as a function of solar price.

Table 6: Total daily cost vs. big-cell power consumption per tower

P_b (in kW)	Total daily cost (Rs.)
10	2500
20	3600
30	4600
40	5420
50	6241
60	6976

or more, we set $R = 100$km. Reliable 24/7 grid supply is assumed to extend upto $R_g = 10$km from the city (industrial area). We solve for R_d in 5.7.1. Transportation cost c_t is estimated based on typical fuel consumption of a single truck and additional labor and maintenance. c_d^0 is based on current diesel prices. To estimate daily operational cost for solar panels used in SSC, we assume a discount rate of 7% and a 20-year payback. The capacity and required area are calculated assuming a power consumption of 300W for a single base station.

For our empirical analysis, we need to first estimate the parameters of the probability density function $p(r)$. We must set A to satisfy:

$$(A/d_b)\int_0^{R_g+R_d} N_0 r e^{-\alpha r} dr + (A/d_s)\int_{R_g+R_d}^{R} N_0 r e^{-\alpha r} dr = 1$$

We can upper-bound the total cost by setting

$$A \approx \frac{d_b}{\int_0^R N_0 r e^{-\alpha r} dr} = \frac{d_b \alpha^2}{N_0\left(1 - (1+\alpha R)e^{-\alpha R}\right)}$$

5.7.1 Crossover boundary behavior

Given our discussion in 5.6, the crossover distance R_d at which diesel becomes unviable compared to solar assumes special importance. Our cost analysis model is predicated on the assertion that it is simpler to crystallize the decision framework into a single distance parameter, than to set up a multi-parameter constrained optimization problem. By characterizing the behavior of the crossover as a function of distance, we are able to realize exactly this goal. To estimate R_d, we plot the behavior of the SSC and diesel cost functions as a function of this distance.

With values from Table 5 and holding $P_b = 20$kW as fixed, Figure 3 plots the behavior of the functions in (9). Note that the point where the two functions intersect gives us R_d. For the current settings, we obtain $R_d \approx 6$km. This translates into a 6km “buffer zone” just beyond the outer extent of reliable grid-supply where diesel is marginally more cost-effective. However, for $r > R_g + R_d \approx 16$km, the SSC model wins out.

Our choice for $P_b = 20$kW in Figure 3 is based on typical power loads on big-cell base stations in India. However, as shown by Balshe [6], in other parts of the developing world such as Latin America, Africa etc., power consumption varies from as little as 5kW to 60kW. With this in mind, we seek to understand how big-cell power consumption affects diesel viability. Figure 4 captures this as a function of the power consumption ratio between a diesel-powered base station and a SSC base station (fixing SSC consumption at 300W). Using the ratio of big-cell power consumption to SSC also allows for continual improvements at the physical layer in the SSC model. We observe that the crossover distance drops off significantly and tapers towards $R_d = 0$ with increasing power loads, thereby ruling out diesel-powered base stations and only considering grid and solar power as viable options. We set c_d^0 at Rs. 50/litre. However, given the pressure on governments (especially India) to phase out fuel subsidies [21], diesel prices are very volatile. Figure 5 captures how this affects R_d, keeping P_b and SSC power consumption loads constant and varying c_{pv} coarsely. We also plot a similar graph with price of solar changing in fine granularity while diesel price changing coarsely, the result is shown in Figure 6. We see a near-linear effect, in both these cases consolidating the belief that with the trend of increasingly unstable diesel prices and decreasing solar prices(often due to subsidies) solar powered architecture wins in the long run.

5.7.2 Total energy cost per tower

We also estimate the total expected cost required to power the base stations. Recall that this is given by $C = C_g + C_d + C_s$ where each cost component was derived in (4)-(8). Since big-cell base stations (either grid-based or diesel-powered) are likely to dominate the overall daily power consumption, it is reasonable to expect a big dependence on P_b. To that end, Table 6 tabulates how the total cost varies with P_b. As before, we have affixed values for the remaining parameters as per Table 5. We also note that the total cost calculation is on a daily basis, and *per base station*. We observe in our model that the overall cost has a roughly linear relationship with P_b and is quite robust to all other parameter values. Our model also accounts for when diesel becomes unviable at which point the total cost only includes grid and solar power. Finally, our estimates are consistent with calculations obtained via other models [28] and validate our assumptions and the model's simplicity.

6. DISCUSSION: WHAT FUTURE HOLDS

In this section, we consider ongoing trends on the power, cost and efficiency characteristics of cellular networks and solar power and discuss the future implications of these trends on the solar vs diesel argument. The general trend in developed and developing countries is showing inclination towards safer and cleaner sources of energy. The recent efforts in this regard include the energy package came into force in the European union in 2009 [33] and ARRA law [37] passed in US in 2009, both of which provide enhanced financial incentives for renewable energy and energy efficient products.

6.1 Future of Solar

Two aspects of the future of solar are noteworthy [33]: (a) trends in solar investments; (b) technology enhancements of PV solar over the long-haul. The solar energy market has witnessed a steady rise in financial investments over the years. While the global clean energy investment in the residential sector remained at the same level worldwide, the ratio of financial investment has shown a enormous increase [33]. This enhancement in investment has resulted in dramatic cost reductions in solar installations and its impact can also be clearly seen in the amount of PV installations in the different countries of the world [5]. The renewable energy sources (RES) market is growing much quicker than the rest of the sectors and the projections give estimates that the present share will be at least tripled in the near future [18, 30]. The RES share has already reached 10 percent of the global energy infrastructure spending and International Energy Agency(IEA) forecasts that up to 2030 the RES share in the investment will increase to between 33 and 52 percent.

The financial investments in solar have also been tightly coupled with technology enhancements. While the useful lifetime of a PV module was initially assumed to be 20 years, recent solar products show only a 10% reduction in maximum power output after 10 years and a 20% reduction after 25 years [33]. The cost of solar power has also been coming down in the past few years and is comparable to other sources in the US [8]. Given the relatively high initial installation costs, third-party vendors have rolled our solar installations with monthly utility payments; this has resulted in a dramatic increase in rooftop solar installations in the US [35]. One metric that has not dramatically improved in the past years is the efficiency of solar panels; the watts/unit area has shown a relatively slow growth, primarily due to the limitations induced by the physics of solar PV.

These trends have the following implications for the future of solar powered cells. First, with the increasing usability of solar panels and ease of maintenance, solar powered cell towers will observe a significant uptake in the coming years. Second, this uptake will also be enhanced with the reducing costs of solar power and enhanced lifetime of solar hardware. When we put this together with Figure 6, the lack in solar price will decrease the crossover distance significantly and it would be feasible to put solar powered base stations nearer to urban areas. Third, the lack of dramatic improvements in solar efficiency will mean that the burden on need for surface area to mount solar panels will not reduce and deployment costs will remain steady.

6.2 Future of Cellular

The site design of the base station site is essential for efficient use of energy in the base station. Mancuso and Alouf [24] highlight three such site designs that work for different environments: (a) The Tower Tube; (b) The Capsule Site; (c) Flexi Base Station. These site designs have been promoted by base station vendors like Ericsson and Nokia and yield significant power and cost savings. Clearly site design also depends on the availability of more efficient, compact and power-conserving cellular hardware. If we get a substantial decrease in the power requirement of the base station it will significantly help in powering the base stations entirely or partially on solar and other renewable energy sources.

In terms of hardware improvements, manufacturers are replacing existing power amplifiers with new efficient devices using digital pre-distortion (DPD) or envelope tracking for wide-band signals. Noticeably, using these efficient power amplifiers allow the deployment of new compact power sites which can be operated with half the power as compared to a regular sites. Recent research confirms that power savings and quality of service enhancements are not conflicting objectives in cellular network design [24].

Operators are also developing new management tools to reduce the amount of operating power with low or zero load. The current systems have shown to be almost as expensive as running at full capacity [2]. This approach has also shown good numbers for smaller community based cellular networks [14]. Operators like Huawai claim that using radio and computational resources efficiently might easily turn into a 40% drop in operational costs [24]. Another important direction towards reducing the power consumption of cellular networks is the simplification of the core internal routing in the cellular network using soft switches which can reduce the energy by up to 60 percent [24].

All these enhancements to cellular networks lead to the common vision of designing low-power and easy to manage cellular networks. To understand the significance of these results, if the power consumption of a cell tower can be reduced to the level of $500W - 1KW$ without sacrificing performance, then powering these devices in a sustainable manner with solar panels becomes an obvious reality with current-day technologies. At low power consumption levels combined with the ever decreasing price of solar, makes the SSC abstraction easily achievable in the near future. If the big cell abstraction is achievable at much lower power levels, even large-scale solar-powered cellular installations which support several users will become feasible. This is supported by our crossover distance computations in the previous section.

7. CONCLUSIONS

This paper describes an economic cost analysis framework for comparing solar powered cellular networks with diesel powered cellular networks to determine the constraints under which solar powered installations are more cost-effective. This question becomes significant given the massive usage of diesel by existing cellular networks in developing regions and the growing need to reduce the carbon footprint of the telecom industry. Using operational data from a large cellular operator, we provide evidence of the gravity of the problem across multiple dimensions: unreliability of the grid, the power demands of a cell tower, the need for diesel from an operator's perspective to meet energy demands and the massive consumption of diesel on a day-to-day basis. Our economic analysis indicates that solar-powered small cells can become a economically viable and cost-effective alternative to the conventional diesel-powered big cells especially in rural contexts. The ongoing movement towards software-defined low-power base stations also strongly supports the push towards the SSC adoption model. Unlike prior studies, we show that diesel transportation does add a significant cost to the diesel operations; farther the distance for diesel access, lower is the operational sustainability of diesel-powered cells. However, if cellular networks, aim to retain the current operational "big cell" model, solar energy becomes a viable option only if the power consumption of future cell towers is reduced.

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