The Unintended Consequences of Power Theft and Restructure:
A Case Study of Gujarat, India.

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Abstract

There is no doubt of the importance to reduce losses and improve reliability of power within a transmission and distribution system. Losses, put simply, represent energy inputs into the system that go unpaid for and excess resources spent in the generation of power, and thus, carry a large financial and environmental burden. The state of Gujarat, in India, is one that has recently gone through a restructuring period where its electricity board was unbundled into seven different entities comprised of a holding company, a generation company, and several transmission and distribution agencies. Supported by a $US 350 million loan from the Asian Development Bank, Gujarat has completely rewired and revamped its current power transmission and distribution structure, and has implemented a large scale '*Yjotigram*' scheme aimed at both providing reliable power to villages, and curbing power theft, as well as gargantuan groundwater abstractions caused by agriculture. With this, technical and non-technical losses have decreased, the sale of reliable power to the commercial and domestic sectors has increased, and Gujarat has become a 'vision of India's future'. Development, however, comes at a price, and here we argue that Yjotigram has not curbed groundwater abstractions but has in fact furthered compromised groundwater resource availability and the state's food security. Increasing reliance on coal power and fossil fuels is also dangerous for Gujarat, particularly in the northern region, given the consumption of water per kWh by power plants. As an area for future research, the water-energy nexus is one where more attention is needed: accurate consumer data, effective -tamper proof-metering, and resilient water and energy infrastructures are all necessary if our society is to develop under increasing resource scarcity and the uncertainty brought about by climate change.

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1. Introduction

The most western state of Gujarat, in India, is a microcosm of the many challenges awaiting our society and the rising-developing world. Hailed as India's Guangdong and a 'vision of [the country's] future' Gujarat accounts for only 5% of India's population but produces 20% of its industrial output and exports, and has in recent years outpaced the country's economic growth rate.[i,ii] Refineries, ports, pharmaceuticals, car makers, manufacturing, energy, and other industries have blossomed in a state that promises reliable electricity, effective politics and policy making, and a workforce that is increasingly urbanized.

The truth, however, is that Gujarat is paying a high price for its development. Although it is true that Prime Minister Narendra Modi has reformed the state and salvaged a financially and technically broken electricity board, it is also true that this has been made possible through a $US 350 million loan from the Asian Development Bank that has furthered Gujarat's dependency on coal as the state's primary source of energy and has set agricultural, industrial, and power production on an irreversible crash course. With the state having reached 80% of its net groundwater available capacity, Gujarat also implemented the Yjotigram or 'enlightened village' scheme, which bifurcated power delivery between agricultural irrigators and villages and small businesses with both the hope of increasing economic activity in villages, and putting an end to ubiquitous power theft, which played a large role in gargantuan agricultural groundwater abstractions. Although accolades for Yjotigram abound due to the increase in economic activity in villages (epitomized by an increase in demand for electro domestic appliances), we have yet to see evidence elucidating the benefits of the scheme with regards to groundwater development. Here we suggest that far from being a scheme that has brought stability to agriculture and groundwater tables in the region, Yjotigram has actually had very little impact in terms of groundwater stability in the region and has in fact made it harder for farmers to earn their daily living from agriculture. In the near future, and with an increased domestic and industrial demand for energy and water resources, we expect droughts and prolonged dry periodicities to aggravate farmer's dependence on groundwater and electricity for irrigation. We also expect coal power plants, particularly in Northern Gujarat, to begin competing against agriculture for water resources. This will be a large point of contention in years to come given the vicious cycle that it generates between agriculture and its dependence on coal power for irrigation.

We first provide a brief description of technical and non-technical losses as well as different ways to 'steal power' in Gujarat. We then provide a brief history of the Gujarat Electricity Board's most recent restructuration, a description of its current structure, and a recent account on losses, revenue, and consumer categories. An evaluation on the Yjotigram's impact on groundwater use for agricultural irrigation concludes our analysis as well as suggesting areas of future research.

1.1 Technical and Non-Technical Losses

Very generally, in this paper losses will be referred to as electricity that is supplied in the system via transmission and distribution systems that is not paid by users. The term '*users*' includes those entities that have established a commercial relationship with the electricity supplier as well as others who consume electricity through unofficial diversion from the system but that do not pay for it.[iii] Technical losses in general are those related to poor power factor (which determines the relative amount of real and apparent power), inductive reactance (related to the system's frequency), resistive losses, overloading, old equipment, and can occur naturally in electricity system components such as transmission and distribution lines, transformers, generator step-up banks, and measurement systems.[iv] Transmission and distribution (T&D) losses are considered technical losses as they are the result of inherent resistance in electrical conductors and transformation inefficiencies in distribution transformers in a T&D network.[v]

Although technical losses are inherent in the distribution of electricity, and all countries experience technical losses at varying degrees, they represent an engineering challenge for power system authorities that can be resolved. This issue is of particular importance for developing countries that are struggling to accommodate dramatic increases in customer load growth. From an engineering perspective, there are many things that can be done to reduce technical losses: transmitting electricity at higher voltages (> 110 kV) reduces the I^2R in long distance transmission, feeders and capacitors can be installed to provide reactive power compensation, transformers and be re-sized and installed to meet and exceed peak load demand, and load factor can be increased so as to reduce energy losses.[iv] For developing countries like India, and states like Gujarat, where there is an existing and extended power distribution system, technical solutions such as balancing current along three-phase circuits provide a great way to reduce losses. Like we will see, Gujarat rewired the entire power system in a way so as to minimize losses and adapted these technical solutions to their own environment, for example, by providing only 8 hours of full three-phase irrigation power to farmers via *a pre-announced and fixed schedule* they were successfully able to increase their system's load factor

Non-technical losses, then, are those caused by agents external to the power system's structure and consist primarily of electricity theft, non-payment by customers, and 'errors' in accounting and record keeping.[iii] Power theft like we will see below, plays a large role in non-technical losses with meter tampering, bypassing of meters, and use of magnets to slow down meters all used as a way to avoid payment.[vi] The literature, like many data sources in India (including India's Central Electricity board) uses different accounting mechanisms for non-technical losses and usually bulk them together into commercial, non-payment, and administrative losses. Historically in India, transmission and distribution losses have been calculated taking into account bills *issued* to consumers as accrued income and not actual *collection*. Thus, through corruption and poor accounting, power theft could go unchecked simply by overbilling.[vi,vii] India uses then Aggregate Technical and Commercial Losses (AG&T losses) as an overall measure of the systems efficiency by taking into account *collections*, thus measuring both technical and commercial losses:[vii]

$$Collection\ Efficiency = \frac{Revenue\ Collected\ (Rupees)}{Billed\ Amount\ (Rupees)} \quad (1)$$

$$Energy\ Accounted = Energy\ Billed\ (kWh) * Collection\ Efficiency \quad (2)$$

$$AG\&T\ Losses = \frac{Energy\ Input\ (kWh) - Energy\ Accounted\ (kWh)}{Energy\ Input\ (kWh)} 100\% \quad (3)$$

In terms of costs, losses in a power system can have a double edge: there is an economic cost and there is an environmental cost. Technical losses represent an economic and environmental cost for a country since the supply power of power is being dissipated in different ways throughout the transmission and distribution system and thus, more inputs (including money and fossil fuels) are necessary and invested in power generation. Simply put, technical losses reduce the ability of a electric utility to be financially sustainable: as losses increase, the amount of power that is unpaid for also increases. Environmental externalities then arise when fossil fuels (including coal and natural gas) and other scarce resources such as water are used to generate power to meet an ever-increasing load demand within an inefficient distribution system.

Non-technical losses have perhaps a more wicked cost than technical losses, and also carry a heavy economic and environmental burden. Since they represent power theft, non-payment, and accounting ‘error’, they are an accurate representation of corruption within a system and the stage of underdevelopment of the distribution structure (i.e., an absence of metering, poor repair and maintenance, and feeders and distribution lines that can be ubiquitously tapped into and exploited). In the sense that users who get free power bribe regulators, theft and corruption are intertwined, and the relationship is mutually incentivized and fostered. From a technical perspective, power theft from distribution lines and feeders has an immediate negative impact on the quality of power and voltage levels for other consumers, particularly those who pay for power, and which represents a subsidy that goes from paying consumers to ‘power thieves’. The environmental externalities here arise in two ways: the obvious one already mentioned above and related to an excess demand for fossil fuels, and another not so obvious one, where power is stolen to exploit a resource, which in the case of Gujarat is water for irrigation. The benefits for curbing non-technical losses for a country like India, and a state like Gujarat, are thus enormous as reducing them would imply more revenue for the electric board, a reduction in technical losses, and a reduced environmental burden. But in a country like India, where metering and cost reflective tariffs are encountered with intense opposition, how does a government monitor and curve power theft? In the next sections we explain in further detail the intricacies of power theft in India, a brief history of Gujarat’s electricity board, reform and the state’s current power system’s structure.

1.2 Power Theft

Power supply is in three main areas 1. Agricultural 2. Residential 3. Industrial. Distribution lines going to many different feeders and provide voltage 220V and frequency 60Hz in 3 phase wires for industrial and agricultural connection while in residential area it is single phase. In all these areas power theft can be done mainly by two methods direct cut from distribution lines secondly bypassing the meters. Direct cut from three phase wires is shown in Figure 1. This image has been taken near agricultural areas. Extra wires have been added to distribution wires to get the incoming voltage supply for their agricultural usage.

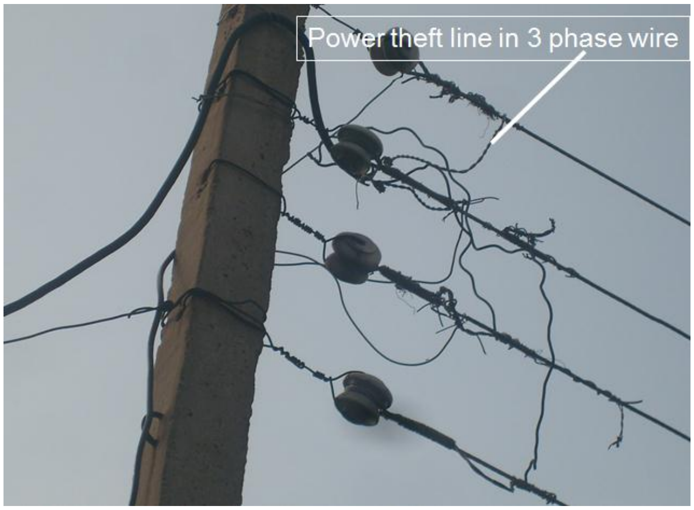

Figure 1. Shows the direct cut from 3 phase wire in agricultural area. Direct cut can also happen in residential area as shown in Figure 2 (*Photo Credit: Deepa Madan*).

Figure 2. Shows the direct cut from one phase wire in residential area (*Photo Credit: Deepa Madan)*.

In residential area meter can be bypassed as shown in figure 3. The Low Service voltage (One phase) line is going to the residential meter. In meter there are 3 lines incoming voltage, neutral and outgoing voltage line to the home appliances. The incoming voltage line provides supply to the meter and the outgoing voltage line determines how much power is consumed in individual home and that appears as meter reading. However people can bypass the meter by getting direct supply from the incoming line.

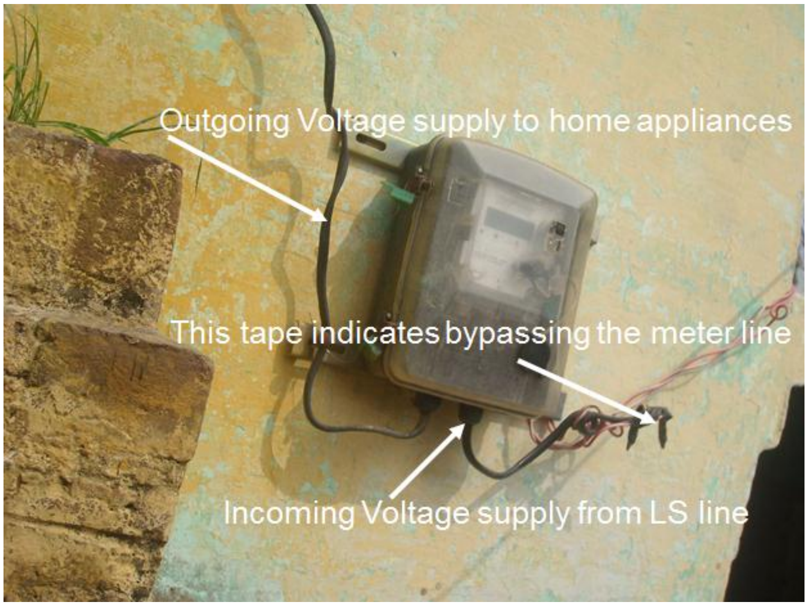

Figure 3. Bypassing the meter in a residential area (*Photo Credit: Deepa Madan)*.

They cut the direct supply line and put their own incoming and outgoing voltage line rather than using the government installed meter incoming and outgoing voltage line as shown in figure 4.

Figure 4. Shows bypassing the meter in residential area (*Photo Credit: Deepa Madan*).

Another way of bypassing the meter is shorting the incoming and outgoing voltage supply line. This is used in industry as well as residential area. One more way of power theft is by bribing the government electricity employee to read much less reading than actual in meter and pay just 30 to 50% of actual bill. This kind of power theft affects the power quality particularly voltage quality.

Rengarajan has explained in his paper how power theft can affect the voltage quality due to load variations. Load is defined as difference between transformer load and consumer load. Voltage is defined as difference between actual voltage and nominal voltage used by consumer. Due to power theft nominal voltage increases therefore voltage fluctuates a lot which affects the power quality badly. In worst case scenario, due to overload, transformer can be damaged and it results in blackout or power cut for long times.[viii]

2. Case Study: 'Vibrant Gujarat'

2.1 A Review of Gujarat's Electricity Board and Reforms

Like many state electricity boards in India, Gujarat's State Electricity Board (GEB) has had a tumultuous past with regards to financing its own growth, and meeting political and population demands, while facing massive technical and non-technical losses. Gujarat's Electricity Board was established in 1960 along with the formation of the state and a mere 315 MW installed capacity.[viii] Today, GEB has a generation capacity of over 12,000 MW and serves over 12 million customers.[ix] [x] However, despite the incredible growth in terms of generation capacity and population served, the GEB has lagged behind in its development mainly because of 1) a lack of efficiency in the generation of electricity, 2) historically high transmission and distribution losses, 3) political interference in the internal functioning of the board, and 4) a dependency on the archaic power sector reforms that preclude change in India.[viii]

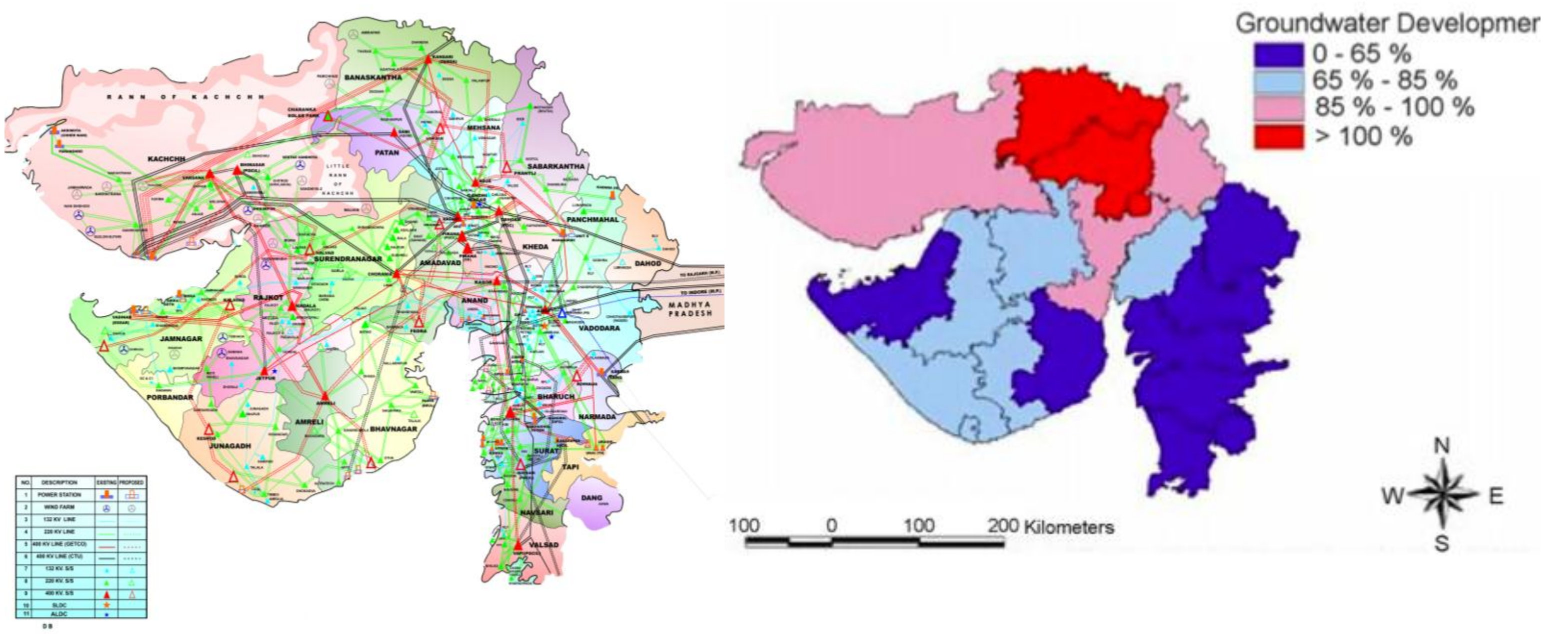

Figure 5. Power Map of Gujarat and Groundwater Development: The map depicts Gujarat's existing and proposed power stations, wind farms, high voltage lines (>110 kV), state load dispatch centers (SLDC), and area load dispatch centers (ALDC). The current structure of Gujarat's power distribution system was financed by a $US 350 million loan provided by the Asian Development Bank. The loan involved a $US150 million 'policy' loan to aid with the restructure of Gujarat's Electricity Board into seven different holding, generation, transmission an distribution agencies, and a $US 200 million 'technical' loan to 'rewire' Gujarat and improve the system's physical structure (*Map Source: Gujarat Energy Transmission Corporation Limited*). Northern Gujarat has reached a stage of 85% of groundwater development, and some regions have reached a stage of 100% groundwater development. This suggests that the annual groundwater draft with respect to annual availability is 85% and 100% respectively. In the near future, and with growing industrial and domestic demand for water and energy resources, agriculture will clash not only with these sectors but also with the energy industry that it relies on for powering irrigation (*Map Source: International Water Management Institute, Delhi, India*).

Prior to Gujarat's electricity reform in 2003, the average capacity factor for all thermal (coal) plants in the state was 62%, a number well below the 80% average capacity factor for coal powered plants and industry standards.[viii] Power theft, antique and obsolete transmission lines, and a lack of effective supervision of High Tension consumers also meant that system losses have always been particularly high with 'Aggregate Technical and Commercial Losses' averaging 32% before GEB's reform and 25% afterwards, with Transmission and Distribution losses, also averaging 23%.[viii,x]

In India, like in much of the world, regulation and efficiency gains in the power sector are subjected to politics, and politicians. The country's electricity act of 1948 specified that State Electricity Boards were autonomous and responsible for the development and operation of generation, transmission, and distribution, but would always work closely with local ministries of finance, coal, railway, water resources, and agriculture. Thus, Gujarat's GEB had traditionally been viewed as an extension of the State Government, and one where decisions over tariffs, operations, personnel, procurement, and investments were seen not from the eyes of a commercial enterprise, but as opportunities for determining political objectives.[viii] Political influence thus coerced the GEB into charging low tariffs to agricultural and residential consumers (cross-subsidizing and passing on the burden to industrial consumers), investing in infrastructure while maintaining a budget deficit, and poor if any enforcement on mechanisms to metering, collecting bills, and no incentives to eliminate large system non-technical losses.[viii]

2.2 Reform

The years of 2000 and 2001 brought about big changes to Gujarat. At the same time as Narendra Modi became Chief Minister, and the state electricity board posted losses of 2542 Rs. Crore (a crore is equivalent to 10 million) the Asian Development Bank approved a sector development program loan to the state comprising of a policy loan of $US 150 million and an investment loan of $US 200 million.[xi] Through restructuring, the loan was mainly intended to reduce operational costs and improve technical efficiencies (reducing transmission and distribution losses) and governance as well as reducing the state's fiscal deficits (by improving the financial health of the electricity board). Other expectations of the program included the expansion of power supply (increasing the number of transmission lines and substations) using private generation capacity, promoting conservation of water and electricity, realizing 100% metering (except for agriculture), and creating a safe investing environment for Gujarat's burgeoning industrial and manufacturing growth. [xi]

In a rare act of political will, and envisioning how an electricity reform could change industrial and economic growth in the state, chief minister Modi first sought debt restructuring and convinced banks and financial institutions to lowering their rates.[xii] In addition, power purchase agreements (PPAs) were renegotiated after finding out that the heat rate had been inflated by independendent power producers (IPPs).[xii] Both debt restructuring and the renegotiation of the PPAs led to savings of 2000 Rs. lakhs (one lack is 100,000) in 2001 and 147 lakhs in 2002.[xii,xiii] Before beginning the board's restructuration however, which was scheduled for 2003, senior officials began a series of 'town hall' meetings and newsletters to keep employees informed about the financial situation of the board and steps that could be taken in the future to improve their situation.[xii] Engaging with workers years ahead of the board's restructuration avoided protests and conflict that could have seriously delayed the ADB loan's implementation.

In 2003 Gujarat enacted an 'Electricity Act' that allowed for the introduction of markets for electricity supply and trading. It also allowed for competition within the transmission and distribution networks where consumers could decide who to buy their power from. However, only large consumers such as industries and commercial establishments were really the only ones with a choice given that distribution of power to rural areas and villages would never be attractive to commercial entities given the potential for losses and inability to measure consumption.[viii] In an open market, an Independent Power Producer (IPP) would serve the large consumers and marginalize agriculture and villages, leaving the state electricity board to service them, jeopardizing once again its ability to recover investments and costs. To avoid discrimination Gujarat's 'Electricity Act of 2003' introduced *Section 68* which stated that the government would pay IPP's to provide subsidized power to small consumers, villages, and farmers. In the absence of liquidity, the State can pay IPP's in bonds but the independent producer is free to raise tariffs to reflect the cost of supply if the state fails to meet its agreements. In addition, with theft being one of the large culprits for transmission and distribution losses *Section 135* of the act specified a punishment of three times the financial gains from theft (*for the first conviction)* and imprisonment for subsequent violations (stealing more than 10 kWh is also punished by imprisonment).[viii] Five regional special police stations have now been created to deal specifically with power theft throughout the state with 500 retired army personnel being in charge of reducing and keeping track of illegal connections.[viii]

2.3 Current Structure

With this, in 2003, and as part of the power reform process there was a 'Transfer Scheme' in which the Gujarat State Electricity board was divided into:

- Gujarat Urga Vikas Nigam Ltd (GUVNL): A *holding* company engaged with the bulk purchase and sale of electricity in Gujarat. GUVNL took over the assets, liabilities and personnel of the residual GEB and currently coordinates the purchase, sale, procurement, import, export and trade of all forms of electrical power.[xiv]

- Gujarat State Electricity Corp Ltd (GSECL): A *generation* company and IPP with approval by the government to undertake new power projects as needed. It owns and manages six thermal (coal) power stations, three gas stations, three hydro-power plants, and a single (1 MW) solar farm. It is currently in charge of developing five new coal projects with a total installed capacity of 4000 MW. [xv,xvi,xvii,xviii]

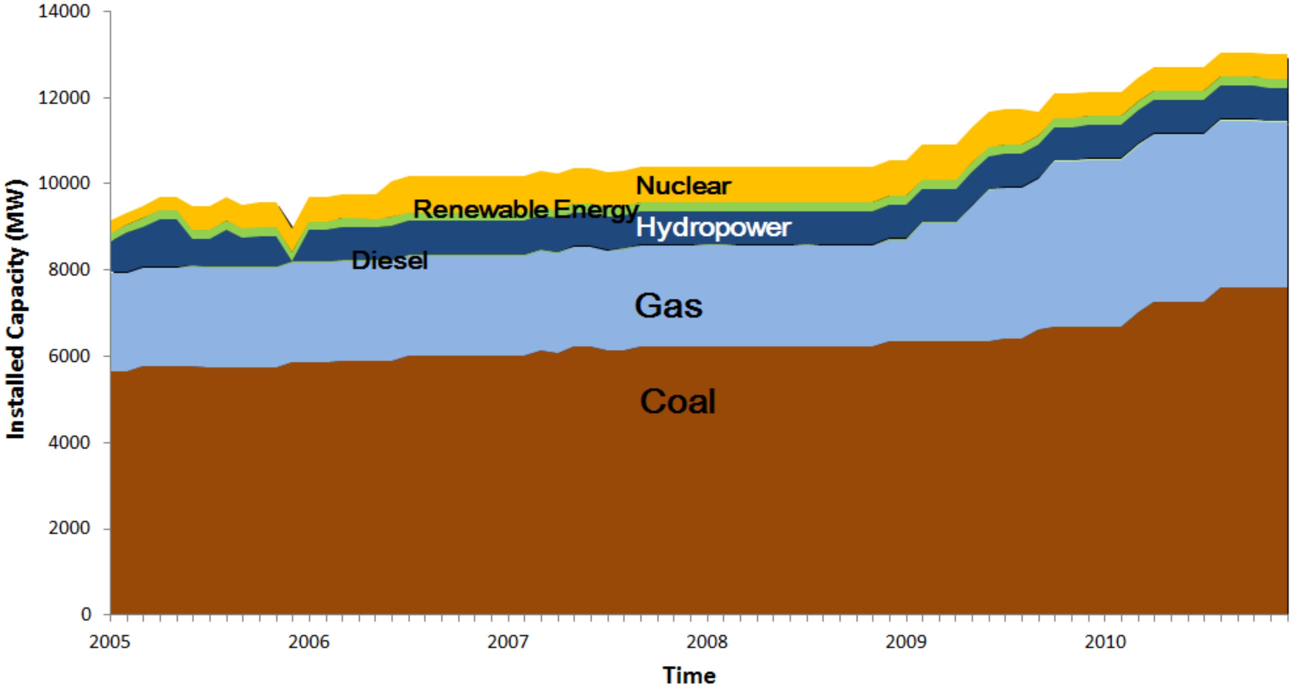

Figure 6: Installed Capacity in Gujarat. Data suggests that coal and natural gas have traditionally accounted for over 60% and 20% of the state's total installed capacity. Although coal has grown steadily over time, natural gas has in previous years surpassed coal's growth rate and currently accounts for over 30% of Gujarat's installed capacity. The region's choice to invest in coal and natural gas as opposite to invest in renewables for the future is a crucial one. The literature suggests that once-trough and recirculating coal (and natural gas) power plants *consume* 0.48 liters/kWh and 4.2 liters/kWh respectively (*Source: 'Water for Energy'. World Energy Council*). Although some of Gujarat's newest power plants are super critical mega plants that are being built next to the sea, older plants still account for a large proportion of Gujarat's total installed capacity (*Data Source: India's Central Electricity Authority*).

- Gujarat Energy Transmission Corp. Ltd (GETCO): The state's *transmission* company that also functions as a load dispatch center (define load dispatch center). It deals with 'day to day' operational challenges such as transmission and distribution losses, quality of power, ageing of equipment and failure rate, and renovation and modernization of equipment.[xix]

- Uttar Gujarat Vij Company Ltd (UGVCL): One of the four state *distribution* companies, this one working in Northern Gujarat. Distribution companies provide information on tariff setting, billing and collection of payments, agricultural irrigation schedules, work on the reduction of distribution, average technical and commercial losses, and work towards the reduction and documentation of energy theft.[xx]

- Dakshin Gujarat Vij Company Ltd (DGVCL), Madhya Gujarat Vij Company Ltd (MGVCL), and Paschim Gujarat Vij Company Ltd (PGVCL) *distribution* companies working in southern, central, and western Gujarat respectively.

In 2008, the ADB completed its restructuration project in Gujarat having accomplished 100% metering (except for agricultural consumers), and installed 5,295 energy audit meters on 11kV, 33kV, and 66 kV feeders. According to reports, this has helped improve the operational efficiency of the distribution system and reduce non-technical losses. A complete revamp of the transmission system was also completed and included the construction of 240 km of 220 kV transmission lines and four 220 kV bays to evacuate power from a new 250 MW coal plant in the Gujarat's Kutch region. Substations were augmented with 100 mega volt-ampere transformers (MVA) and 270 km of 220 kV, and 600 km of 66kV transmission lines were laid across the state together with 50 new 66/11 kV substations to strengthen the transmission infrastructure throughout the state.[xi]

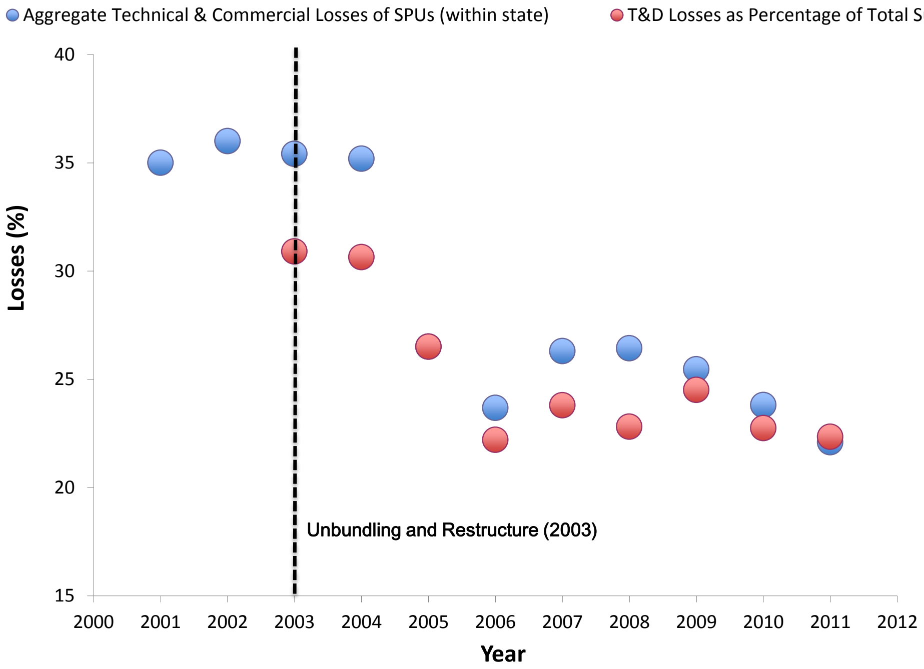

Figure 7: Transmission and Distribution (T&D) and Aggregated Technical and Commercial Losses (AG&T Losses): Historically in India, transmission and distribution losses have been calculated taking into account bills *issued* to consumers as accrued income and not actual *collection* of fees. Thus, through corruption and poor accounting, power theft could go unchecked simply by overbilling. India uses then Aggregate Technical and Commercial Losses (AG&T losses) as an overall measure of the system's efficiency by taking into account *collections*, thus measuring both technical and commercial losses (described in detail above). The deployment of high voltage transmission lines, resizing and replacing aging transformers and distribution lines, installing substations and over 3,200 single and three-phase meters at feeders has allowed for a decrease in AG&T losses throughout the state. In addition, Gujarat has successfully managed to implement the Yjotigram scheme, which provides 8 hours of full three-phase power to farmers on *a pre-announced schedule* (generally at night), this has allowed them to take control over their load factor, a metric which until very recently had been impossible to manage (*Data Source: Gujarat Urga Vikas Nigam Ltd (holding company) and India's Central Electricity Authority 2011-2012 Annual Report*).

Aside from overall system improvement, the ADB's project also focused on upgrading the distribution systems of Kheda, Rajkot, and Mahesana in Northern Gujarat, the driest and most water scarce region in the state. It built a new 2X315 MVA 400/220 kV substation at Rajkot, established line in-line out (LILO) for a 400 kV (60 km) transmission line at Rajkot, constructed 15 new 66/11 kV substations and laid out 150 km of 66kV lines, 4400 km of 11kV lines, 3,400 km of 0.4 kV distribution lines, replaced 24,000 transformers (12,000 transformers with 100 kVA and 12,000 transfomers with 63 kVA ratings) and procured the distribution and installation of 3200 single and three phase meters. Figure 5 (above) depicts the current structure of Gujarat's transmission and distribution system.

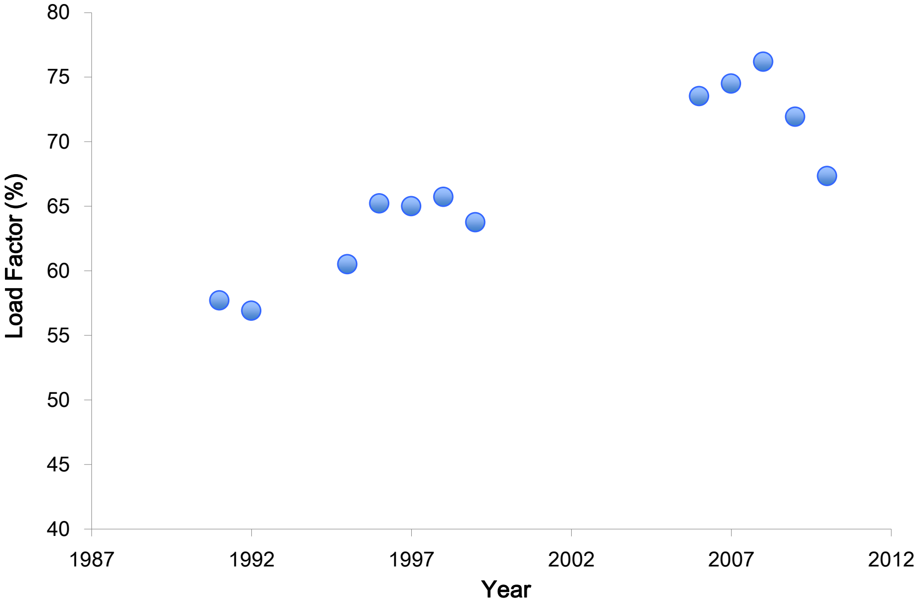

Figure 8. Load Factor: The load factor is a fraction representing how much generation capacity is required in a system versus how much electricity is consumed on average. From a utility's perspective a higher load factor is better since revenues are roughly proportional to average production but fixed costs are proportional to maximum demand (*Source: Duncan Callaway. Electric Power Systems 254 Class Notes, UC Berkeley*). In a constant pursuit to increase load factor Gujarat's utilities were benefited by the Yjotigram scheme which usually provides *overnight* three-phase power to farmers on a pre-arranged schedule (*Data Source: India's Central Electricity Authority)*.

Over the last five years of available data, the consumer class with the fastest annual growth rates within Gujarat have been the commercial sector (11% per annum), domestic consumption (9%), sale of power outside the state (8% per annum), industry (7%), and agriculture (6%). The fact that the commercial and domestic sectors are thriving relative to other consumer classes lays to evidence the success of the Yjotigram scheme (described in detail below) to provide reliable power to villages, households, and the commercial sector that is usually comprised of small businesses, schools, universities, and hospitals. In terms of sale of power however (million kWh; MkWh), agriculture and industry still consume the lion's share of the total accounting for over 70% of total sales, with 30% and 40% attributed to them respectively.

Figure 9. Sale of Power in Gujarat by Consumer Class: Over the last fives years of available data, the consumer classes with the fastest annual growth rates within Gujarat have been the commercial (11% per annum), and domestic classes (9%). In terms of sales of power however (million kWh; MkWh) agriculture and industry still consume the lion's share of the total accounting for over 70% of total sales, with 30% and 40% attributed to them respectively. Like we will see below, the fact that the commercial and domestic consumer classes have posted such incredible growth rates speaks to the success of the Ygotigram scheme in providing 24 hours of full phase power. However, at the same time as agriculture is the second largest consumer in the state, its consumption is subsidized by all other consumer class sectors (Figure 10) (*Data Source: India's Central Electricity Authority)*.

In terms of finances however, the level of cross subsidization between agriculture and all other sectors has hardly improved: agriculture is the second largest consumer of electricity yet it pays the least per kWh. Although an analysis of cross subsidization is beyond the scope of our analysis, one could sugest that the commercial, transportation, and 'out of state' consumer classes are the ones who carry the largest burden of the cost consuming the equivalent of 20%, 5%, and 50% of agriculture's total consumption (MkWh) yet, transport and commercial pay three *times* the amount, and the domestic class pays *twice* the amount that does agriculture per kWh. This highlights the still long road to develop appropriate incentive schemes that can make agriculture adjust its behavior, through prices and water/energy saving technology, in a world with ever more scarcity of resources.

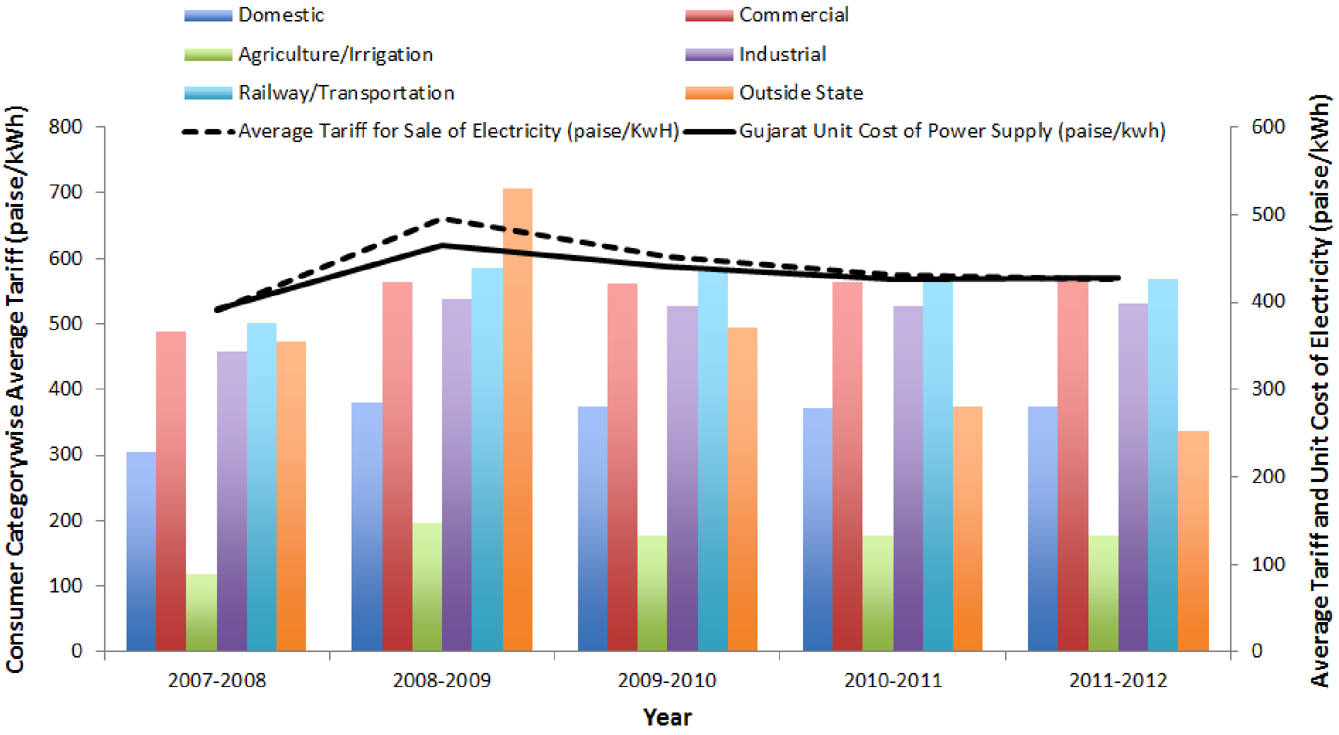

Figure 10. Electricity Tariff by Consumer Class: Commercial, transportation, and 'out of state' consumer classes are the ones who carry the largest burden of the cost consuming only the equivalent of 20%, 5%, and 50% of agriculture's total consumption (MkWh) yet, paying three times (transport and commercial classes) and twice the amount (domestic classes) that agriculture does for electricity (per kWh). One success of the Yjotigram scheme, however, has been that the tariff (in paise) per kWh produced has stayed marginally above the cost per kWh. In addition, Gujarat's electricity board has been able to meter eletrcitity for all sectors (except agriculture) and thus has been able to maintain financial solvency by keeping the average tariff slighlty above the average cost of production (per kWh) (*Data Source: India's Central Electricity Authority*).

2.4 Yjotigram Scheme: 'Lighted Village'

Although not supported by the ADB because of an absence of metering on irrigation, the Yjotigram or '*Lighted Village*' scheme is what has truly popularized Gujarat's electricity reform transition, earning the state all sorts of accolades in terms of water and energy management.[xxi ,xxii] Gujarat is a state characterized by wet and dry periodicities, high spatial hydrological variability, extreme events, and drought. Being a state where over 60% of the population is rural and over 50% depends on agriculture for a livelihood rural electrification, and the use of groundwater as a buffering system during drought, has played a dramatic role in improving agricultural production and people's lives. During the 1950's and 60's submersible electric pumps began replacing diesel pumps for irrigation both because of their cost and horsepower advantage in chasing receding tables, and thus, submersible pumps lead Gujarat's irrigation growth (according to reports 90% of the pumps installed are electrified).[xxii] In the mid 1980's widespread groundwater depletion reached crisis (salinity, high fluoride concentration, and scarcity) in North Gujarat, the Kutch region, and the hard rock areas of Saurashtra.xxii In the decades that followed numerous interventions to meter both electricity and water used failed time and again to earn farmer's support. Meter reading and billing implied high operations and transaction costs for the electric board, would raise electricity tariffs for farmers, and would inevitably always led to corruption. Today, over 65% of the pumps being used in the state are electrified, and 90% of all new pumps installed are electrified both because of the horsepower required to extract groundwater from ever increasing depths and because of the the relative cost advantage of using subsidized electricity as opposed to diesel.[xxii,xxiii]

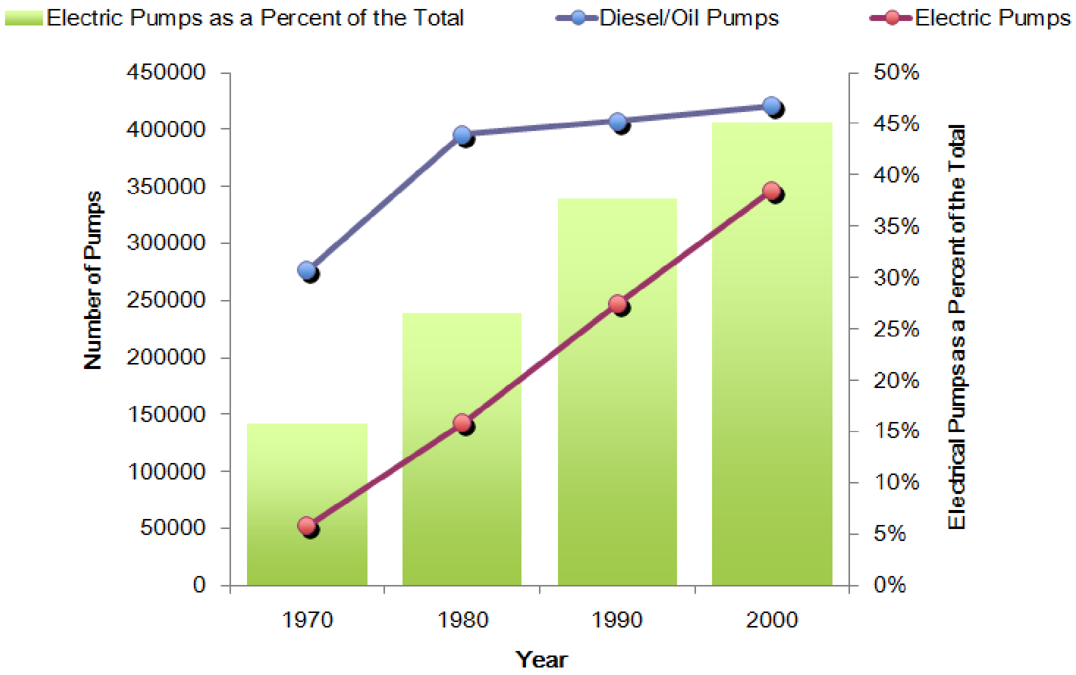

Figure 11. Pumps for Irrigation: Since India's 'Green Revolution', the pace of rural electrification in the country has come accompanied by a growth in electrified irrigation. In three decades, electrified irrigation in Gujarat has gone from 15% of all installed pumps in the state in the 1970's, to 45% by 2000. Today, 65% of all electrified pumps in the state are electrified, and 90% of all new pumps installed are electrified both because of the horsepower required to extract groundwater from ever increasing depths and because of the relative cost advantage of using subsidized electricity as opposed to diesel (*Source: International Water Management Institute, Data Source: Agriculture and Co-operation Department – Government of Gujarat*).

As a last resource to curtail electricity demand from irrigation, Gujarat's Electricity Board reduced the power supply to agriculture: early in 2000 the GEB began providing only 10-12 hours of 8 three-phase power to agriculture to be used by motors and pumps, and provided singe-phase or two-phase power the rest of the time. Villages, small businesses and feeders were all connected to the same feeder. However, with power theft being rife in India, farmers began using phase-splitting capacitors to convert single and two-phase power into three-phase power to run their pumps uninterruptedly. Power theft reduced the quality of power and voltage downstream and affected daily life in villages and small businesses ubiquitously. Split phase capacitors, or '*totas*' as farmers call them in Gujarat would provide low and fluctuating voltages, which would result in the frequent burn out of motors. Evidence from Gujarat, India, and other developing countries around the world also suggest that in places with frequent power outages and large voltage fluctuations, farmers buy oversized pumps so as to maximize abstractions during periods when electricity is available and to minimize motor burnout due to supply fluctuations.[xxii,xxiv] In addition, oversized pumps are bought under the expectation that farmers are competing against a neighbor for a common resource that is ever more growing scarcer.[xxiv] Although farmers do have an incentive to a buy a larger pump (competition for resources and subsidized electricity costs), there is absolutely no incentive for farmers to use a smaller, more optimal pump.

On 2006, the ‘Jyotigram’ scheme was implemented in 95% of Gujarat’s 18,000 villages whereby a flat rate-tariff was supposed to be raised gradually to reflect the *average cost* of power consumed by a tube well, low-cost off-peak power was to be provided at night to reduce average costs, and ‘intelligent-rationing’ was to be implemented as to best meet the needs of farmers.[xxiii] With *Yjotigram*, Gujarat was completely rewired with the deployment of 48,852 km of high-tension lines and 7,119 km of low-tension wires, 12, 621 new transformers and 1,470 specialized ‘anti-theft’ transformers designed to shut off power supply on the entire feeder if the load increased above a minimum level.[xxii] One million new electricity poles, 180,000 km of electricity conductors, 610,000 km of low tension cables, 30,000 tones of steel production, and meters on distribution transformers were installed on both sides of the feeder to improve energy use, to provide data, and better management. The entire project, without support from the ADB, accrued an investment of $US 290 million.

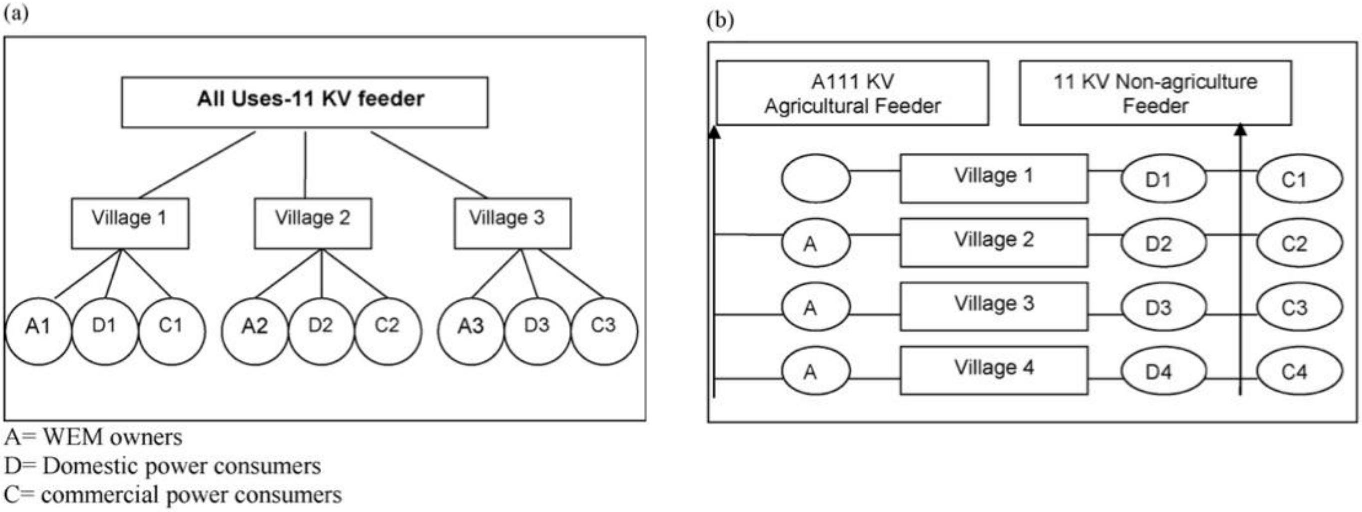

Figure 12. Feeder Separation: Before 2006 (a), 11 kV feeders would service 2-3 villages including their electric pump owners (irrigation), domestic, and commercial consumers. Yjotigram bifurcated the feeders providing a separate 111 kV (b) for electrified irrigation (agriculture) and a separate 11kV feeder for domestic and small-commercial consumers (*Source: International Water Management Institute)*.

With these changes, 18,000 villages now receive *24* hours of three-phase power supply for domestic use, schools, and small businesses, and farmers now receive *8* hours a day of three-phase uninterrupted power on a pre-announced schedule.

Since 2006 there have yet to be peer reviewed and published studies depicting the impact that Jyotigram has had on groundwater levels, particularly in Gujarat’s northern and Kush regions. However, in terms of the power industry structure, GEB has improved its control over finances by providing a flat-tariff (albeit subsidized) with a tight control on the volume of farm power supply, which it adjusts successfully, and with the support of farmers. Villages, households, and small businesses have also blossomed once again due to Jyotigram (as depicted in the growth in demand from both domestic and commercial class users above) with reports suggesting that conditions in households, hospitals, universities, and public services (for example, street lightning and telecom) have dramatically increased.[xxii,xxv] According to reports, power cuts and voltage fluctuations, which were endemic, are now virtually non-existent.[xxvi]

Small businesses that would work on diesel engines during power outages (for example flour mills, barbers, cold-drink sellers) can do more work, have seen 10-20% increase in businesses, and have reduced cost with reliable and cheap three-phase power as compared to diesel. Surveys and studies suggest the rice mills, shops with perishable foot times, computer training centers and many others suggest that a reliable source of power has created more local employment opportunities in villages accompanied by a reduction in maintenance and repair cost of equipment, breakdowns, and working capital requirement.[xxvi] Inverters and gen-sets, which were ubiquitously used during power outages have now begun disappearing.[xxii,xxvi]

Despite these accolades, there has yet to be a peer-reviewed publication regarding the stabilization of Gujarat's groundwater table and changes in the quality of life in households and productivity of small businesses and industry.

3. The Unintended Consequences of Power Theft and Restructure

Unavoidably, demand for electricity is linked to climate. In Gujarat, with irrigation for agriculture accounting for over 30% of total demand, the monsoon's variability has a deep impact on the demand for both electricity and groundwater resources. There are two main cropping seasons in Gujarat, the wet season (Kharif) which consists of growing rice and other cereals (bajri and maize) using the monsoon rains (June through September and accounting for over 90% of total annual precipitation), and the dry season (Rabi) which uses the monsoon to prepare soil moisture and to recharge the groundwater tables that will be used for irrigation during the wheat cropping season. On aggregate, rice and wheat account for over 20% and 40% of Gujarat's total agricultural production and thus, the monsoon rainfall is critical to the productivity of 60% of the state's agricultural output. Figures 13 below depicts how the arrival of the monsoon is related to both peak demand and supply of power: as the monsoon arrives in June its intensity increases steadily through September while both monthly peak power and energy supply decrease. During these months both power demand for irrigation and air conditioners, on average, decrease.[xxvii] As the monsoon leaves Gujarat, and the dry wheat-cropping season begins, peak power and supply both increase, as they have to supply power for irrigation.

Precipitation variability, climate change and extreme events also play an important role in Gujarat's water-energy nexus. The literature suggests that structural changes in the monsoon (delay of the monsoon) and the increased likelihood of extreme events (persistent drought and floods) have been observed both in Gujarat, and the rest of India.[xxviii,xxix] Although the monsoon in Gujarat experiences prolonged dry and wet periodicities, the years of 2006, and 2009 give us an insight into the relationship between structural changes in the monsoon, extreme events, and the supply and demand for power (*please note that I have yet to find good data for the flood of 2006!*).[xxx]

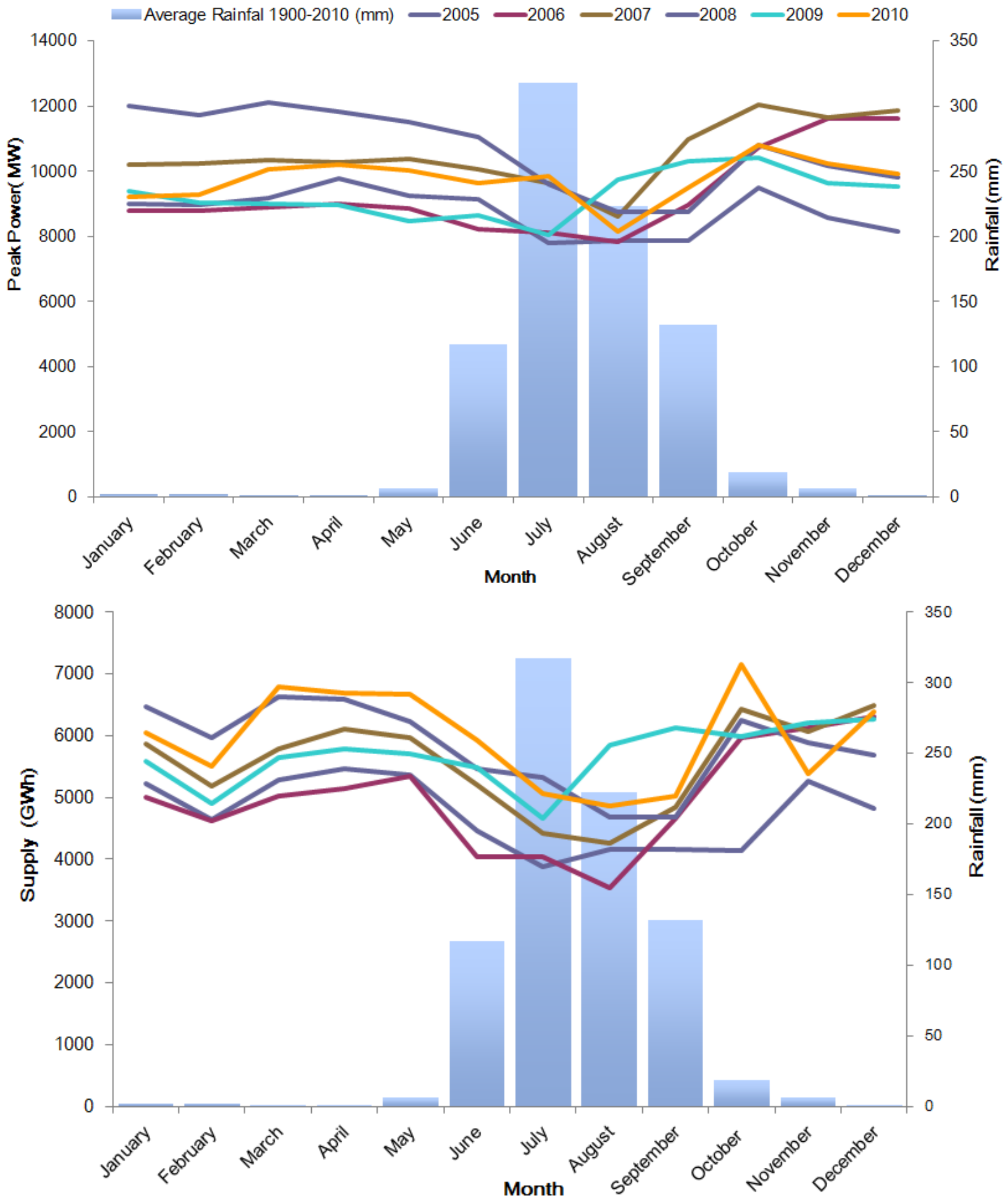

Figure 13. Peak Power (a) and Power Supply (b): The Indian monsoon in Gujarat lasts from June through September and drops over 90% of the total annual precipitation in four months. There are two main cropping seasons in Gujarat, the wet season (Kharif) which consists of growing rice and other cereals (bajri and maize) using the monsoon rains, and the dry season (Rabi) which uses the monsoon to prepare soil moisture and to recharge the groundwater tables that will be used for irrigation during the wheat cropping season. On an average monsoon year, supply of power between June and September is much lower as the monsoon provides both cool air to replace air conditioners and rainfall as irrigation. The charts above also depict the impact that a deep and prolonged drought (2009) can have on (a) actual power supply, and (b) peak power: power supply is high and peaks during the monsoon and persists throughout the cropping season for both rice and wheat. Extreme events stress such as droughts affect both groundwater availability and a power system's ability to provide power. (*Data Source: Indian Institute of Tropical Meteorology*).

One of the worst floods Gujarat has ever experienced occurred in 2006 when heavy rainfalls in July and August affected industries, farmers, traders and service sectors with massive losses in terms of lives, assets and properties.[xxxi] The loss of life and assets were publicly blamed on the poor management of reservoirs and hydropower production facilities that did not optimize the release of water during the floods.[xxxii] Besides the obvious impact on households, farmers and other industries, Gujarat's electricity board was coerced into supplying basically free power to affected communities for the rest of year, which they were able to do with the surplus of power and the consequent revenue that was provided by the sale of hydropower. [xxxi]

More obvious however is the relationship between extreme drought and demand for power. In 2009, Gujarat experienced a prolonged drought that failed to both meet crop water requirements for rice during the wet season and provide soil moisture and groundwater recharge for wheat during the Rabi dry season. On an average monsoon year, supply of power between June and September is much lower as the monsoon provides both cool air to replace air conditioners and rainfall as irrigation. During a drought however, demand for power is high during the monsoon and persists throughout the cropping season for both rice and wheat (Figure 13). With impending climate change, we expect to see continued dry and wet periodicities, a delay of the monsoon and an amplification of extreme events. However, as the region depletes its groundwater table, the ability of farmers to *buffer* a drought or a prolonged dry periodicity through the use of groundwater will be reduced. In the face of drought and receding groundwater tables more energy will be required to pump water, but as we will see, agriculture and Gujarat's power sector will come to a clash if something is not done (beyond rewiring the power sector) to curve agricultural demand for water and energy, as well as the power sector's thirst for fossil fuel resources.

3.1 Evaluating the Environmental and Agricultural Impacts of Yjoigram

In 2011, the Columbia Water Center (CWC) did the most recent study to explore groundwater depletion in Gujarat. Focusing on northern Gujarat and the city of Mehsana, one of the largest cities in the state, the CWC found that an average well here could now only irrigate about 60% of their command area during the dry season (wheat) and interviews with farmers in the region suggested that water for irrigation was only expected to last for about six more years.[xxxiii] At the same time, the CWC and a recent USAID study suggest that there are, on average, 5 horsepower's of installed capacity per acre.[xxvii] With water tables declining steadily in the region over the last 15-20 to years (currently the groundwater table is being depleted over 9 feet per year) it is important to evaluate: 1) whether the Yjotigram scheme is actually helping reduce groundwater withdrawals and stabilize aquifers, and 2) whether providing 8 hours of full phase power is sufficient to meet crop water requirements during the dry season (wheat). Wheat is an important crop for Gujarat given that it represents over 60% of the state's agricultural output.

The Food and Agriculture Organization of the United Nations suggests that one season of wheat production requires between 450 mm to 650 mm of water, per acre, depending on the climate and length of the growing period.[xxxiv] For India, it is suggested that an acre of wheat would require 600 mm per cropping season (120 days from October through January). With this information, we used the mechanical energy balance given (4), to determine the optimal pump requirements with receding water tables.

$$W_s = g(z_1 - z_2) + \frac{1}{2}(v_1^2 - v_2^2) + \frac{p_1 - p_2}{\rho} + 4f\frac{\Delta L}{D}\frac{v_{avg}^2}{2} \qquad (4)$$

In this equation, W_s (m^2/s^2) is the shaft work, which after accounting for efficiency becomes the work required by the pump W_p (m^2/s^2). It is taken that at the top of the well, $z_1 = 0$m and v_1 will be approximated as 1.7 m/s, which is the optimal velocity in the process line or for pump discharge of a non-viscous fluid.[xxxv] At the bottom of the well, $z_2 = -80$m as the starting depth and $v_2 = 0$, and it is assumed that the pressure drop (Δp) is negligible as both sides have atmospheric pressure. In calculating frictional losses, the average velocity (v_{avg}) was approximated as the discharge velocity and the pipe length (ΔL) was assumed to be 40m longer than the depth to account for any extra pipe requirements, giving a starting value of 120m. The friction factor (f) was determined by use of the Reynold's number and empirical data.[xxxv] Using these simplifications and accounting for efficiency, we get:

$$W_p = \frac{1}{\eta}\left[g(-z_2) + \frac{1}{2}(v_1^2) + 4f\frac{(-z_2 + 40)}{D}\frac{v_1^2}{2}\right] \qquad (5)$$

To determine the diameter, the volumetric flow rate was first approximated by the fact that wheat in the dry season requires 600 mm of water per acre in 120 days of 8 hour pumping time. This is calculated to be 7×10^{-3} m^3/s and we can divide by the velocity to obtain the required pipe diameter. We determined the pipe diameter to be a one-inch nominal pipe size (24.3 mm), which is in good agreement with optimal pipe diameters from empirical relationships in literature.[xxxv] The pump work (m^2/s^2 or J/kg) was calculated with a 40% efficient pump and when multiplying by the mass flow rate (kg/s) we get power in watts, which we can convert to horsepower. This mass flow rate was obtained by simply multiplying the volumetric flow rate by the density of water. Now, using a starting depth of 80 meters, which is the current groundwater depth in northern Gujarat, and estimating a depletion rate of 9 feet (2.7 meters) per year, we obtain:

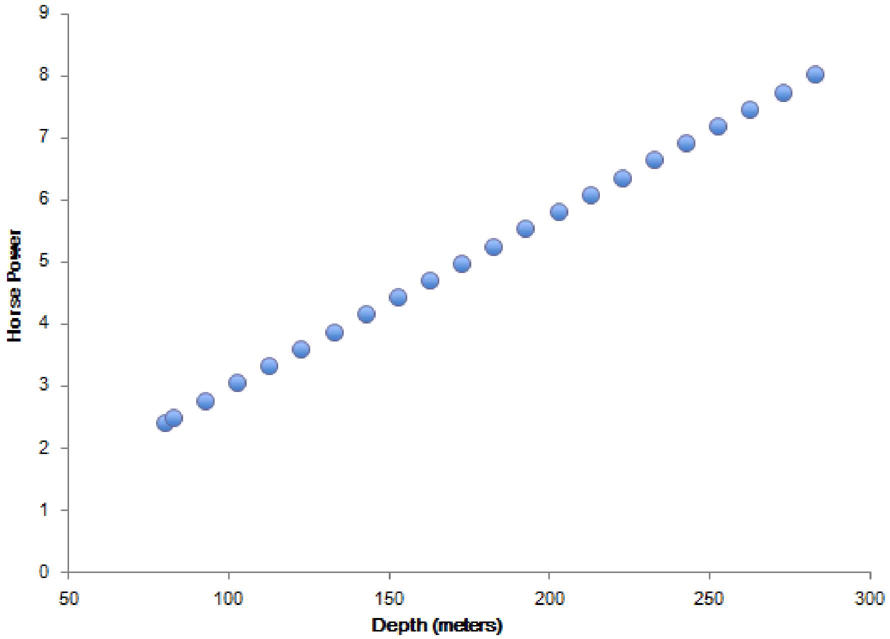

Figure 14. Relationship Between Depth and Horse Power: Using a simple mechanical energy balance, this analysis suggests that starting at 80 meters one would only need a 3 horsepower pump to irrigate wheat in Gujarat during the dry season, but would require a more powerful pump at lower depths. According to our results a 5 horsepower pump would only seem optimal at a depth of 150 meters. Like we have explained before, it is likely that farmers in Gujarat, like many other places in the world, oversize their pumps so so as to maximize abstractions during periods of available electricity and to minimize motor burnout due to supply fluctuations. Oversized pumps are also bought under the expectation that farmers are competing against a neighbor for a common resource that is always growing scarcer. Although farmers do have an incentive to a buy a larger pump (competition for resources and subsidized electricity costs), there is absolutely no incentive for farmers to use smaller, more optimal pumps, for a particular head (depth).

Another interesting variable to study is the time per day required to pump the necessary volume of water in 120 days with a 5hp pump. The farmers are given 8 hours a day to pump water, but as we established that they are using larger pumps than necessary, they are in fact able pump the required water in fewer hours. We first assume that the installed piping system, including pipe diameter, will temporarily remain the same due to the high associated costs. We can then determine the pumping time required from calculating an updated velocity for each depth by rearranging (5) as follows:

$$v_1 = \sqrt{\frac{\eta W_p + g z_2}{\frac{1}{2} + 2f\frac{(-z_2+40)}{D}}} \tag{6}$$

By calculating the velocity from (6) and by using the pipe diameter, we can determine the volumetric flow rate required for each depth. The volume of water required is held constant as previously given and, therefore, the time per day required to supply this volume over 120 days can be calculated. These results are shown in the figure below for the receding water table levels:

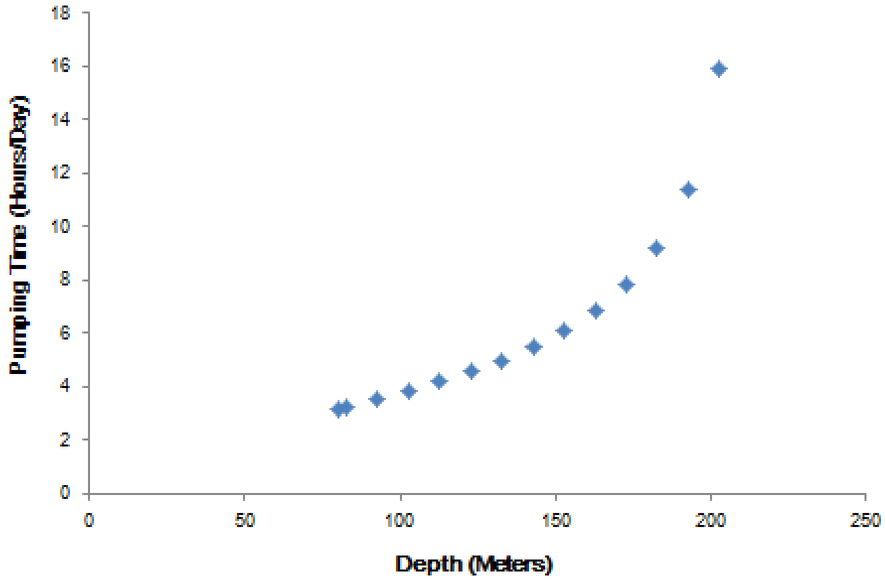

Figure 15. Depth and Pumping Time: Using equations (4) and (5) and solving for velocity we can use our assumptions for pipe diameter, and volume, to calculate the pumping time required (hours/day) to meet crop water requirements for wheat during the dry season. The results suggest that with a 5hp pump farmers can still meet their crop water requirements with under 8 hours of pumping but will be unable to irrigate their fields in the future for two main reasons: 1) salinization will most likely occur as soon as depth to water reaches sea level, and 2) farmers will have to invest in ever larger pump sizes as depth increases.

This analysis suggests that there are only two limiting factors for farmers to regulate their groundwater abstractions: 1) reaching the saline depth of water at which agriculture would be irreversibly halted in the region, and 2) the cost of investing in ever more powerful pumps to chase the receding groundwater tables. As we have seen, Yjotigram does not address either of these two issues by 'only' providing 8 hours of three-phase power to agriculture. We suggest here that the investments made by Yjotigram have only secured the reliability of power through which agriculture will continue exploiting the groundwater resource in the near future.

3.2 Fighting for Water: The Vicious Cycle of Agriculture and Power

With over 60% of Gujarat's total power being supplied by coal, the state, like the rest of India, has generated an overdependence on fossil fuels. It is true that the unbundling of Gujarat's electric board has provided an incentive for the different agents involved in power distribution to reduce both AT&C losses, T&D Losses, increase the load factor, and rewire the system in a way that meets the demands of the population. However, at the same time as the ADB provided a loan to rewire Gujarat and the Yjotigram scheme was implemented, the state also built six new coal power plants, three of which are located in the water scarce region of Northern Gujarat.

The literature suggests that the water-energy nexus involved in coal power production is a complicated one. Waste heat discharged from power plant cooling systems can raise the temperature of rivers and lakes, and wastewater from boilers and cooling systems almost always carry heavy metals, acids, organic materials, and suspended solids.[xvii] Coal power production cooling systems usually employ either once-through cooling or closed-cycle cooling systems. Where there are vast fresh (rivers, lakes, or groundwater) and salt water resources once-through cooling systems prove to be economically advantageous: water is withdrawn from the source and then discharged at a much higher temperature. Closed-cycle wet cooling systems (recirculating systems) on the other hand rely on evaporation to dissipate waste heat through either cooling towers or ponds with dry cooling towers (which are considerably more expensive) being popular in water scare regions.[xvii] Coal power plants burn coal to generate steam, and the system's efficiency depends on the turbine's outlet pressure. The role of the cooling system (i.e., the main role of water) is then to reduce the turbine's outlet pressure to increase efficiency with once-through cooling systems *consuming* 0.38 liters of water per kWh produced, and with closed-cycle wet cooling systems *consuming* 4.20 liters per kWh produced.[xvi] Worth noting is the fact that this is only water being used in electricity production, and if one were to take into account the amount of water that is required for dust suppression, drinking and sanitation, ash handling, flue-gas desulfurization, and coal *mining*, these numbers would be substantially higher.

Knowing this, the choice to further this overdependence on coal in Gujarat's Northern region (and all of India) is then a dangerous one given the water embedded in power production, and the growing scarcity of the resource in the region. If we take into account only the coal power stations in the northern and water scarce regions of the Kutch, Mehsana, Amadavad, Sabarkantha, and Kheda, the total installed capacity is 3080 MW, with the largest thermal plant being the Wanakbori plant (1270 MW), conveniently installed on the banks of the Mahi river in Kheda. Newer and much larger plants such as the TATA UMP plant (8000 MW) and the Mundra Adani plant (5000 MW) in northern Gujarat have been installed in the gulf of Kutch to allow the plants to use sea water, yet, they are connected to the rest of the system through the large and recent investment in Gujarat's power transmission system. The latter are not taken into account in our analyses.

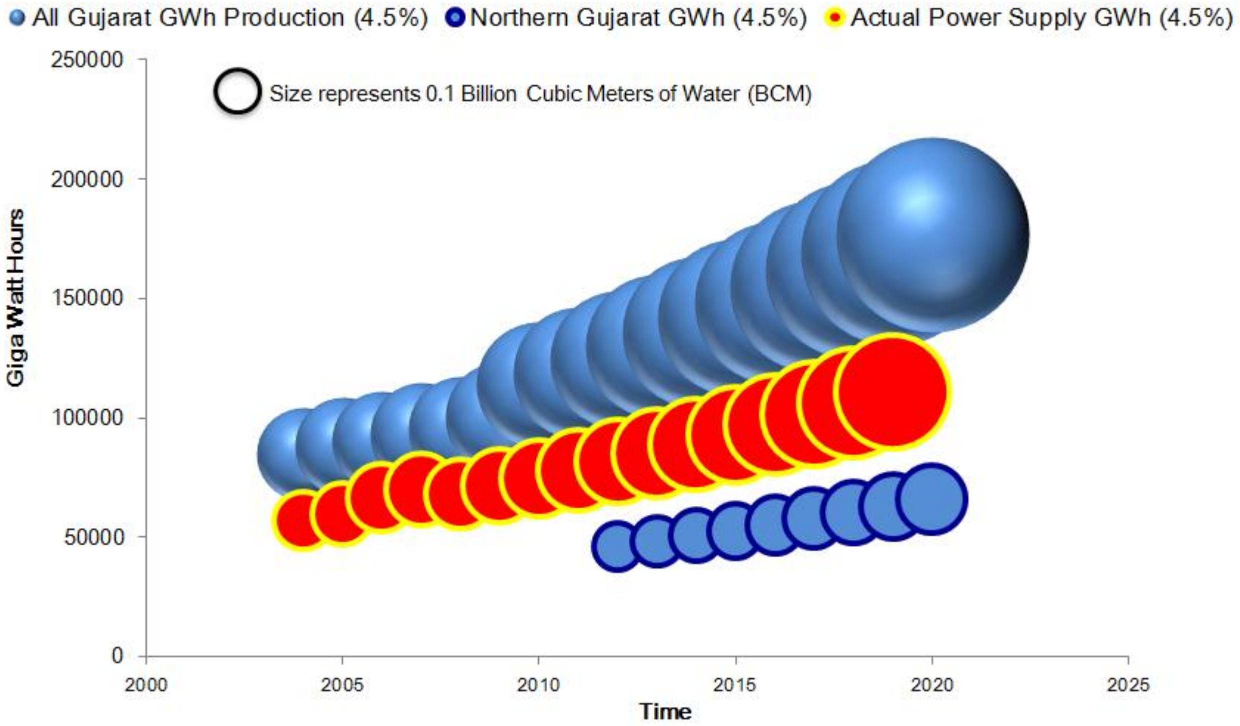

Figure 16. Water and Electricity: Assuming a plant's efficiency to be 35%, with a 60% capacity factor, and an annual growth rate of 4.5% in installed capacity, we expect Gujarat and its northern region to be producing 180,000 GWh and 74,000 GWh respectively by 2020. In terms of the installed capacity of once-through vs. recirculating systems, and using the United States as a comparison, we assume that 40% of the thermoelectric plants in Gujarat use once through systems. These numbers would represent an annual groundwater withdrawal of 0.5 billion cubic meters (BCM) per year by 2020 for Gujarat's total coal installed capacity, of 0.20 BCM per year for northern Gujarat's coal power installed capacity, and of 0.30 BCM per year by 2020 in terms of actual supply of power.

Assuming a plant's efficiency to be 35%, take it to be working with a 60% capacity factor, and assume coal's annual growth in the region to be a balanced 4.5% (the actual growth rate has been 6% per annum) in installed capacity, we expect Gujarat and its northern region to be producing 180,000 GWh and 74,000 GWh respectively by 2020. In terms of the installed capacity of once-through vs. recirculating systems, and using the United States as a comparison, we assume that 40% of the thermoelectric plants in Gujarat use a once through system. These numbers would represent an annual groundwater withdrawal of 0.5 billion cubic meters (BCM) per year by 2020 for Gujarat's total coal installed capacity, of 0.20 BCM per year for northern Gujarat's coal power installed capacity, and of 0.30 BCM per year by 2020 in terms of actual supply of power. In a state that has already reached 80% of its groundwater potential, and with a net groundwater availability of 15 BCM, these estimates would suggest a net depletion of 3%, 1% and 2% per year of the state's total groundwater resource.[xxxvi]

4. Discussion

What are the unintended consequences of power theft and restructure?

One cannot consider environmental externalities and financial deficits to be unintended consequences of power theft. Farmers, households, and large industries who engage in bribery, corruption, bypassing meters, illegally connecting to lines, or installing phase splitting capacitors are largely aware of what they do. They are aware that their neighbors pay electricity fees that subsidize their own consumption, they experience power outages and voltage fluctuations caused by an antique and abused power distribution system, and live in an environment that is ever more difficult to live in with increased ambient pollution and receding water tables. The unintended consequences of power theft are the arrival of a political motivation to restructure and rewire a power system amassed with popular support. Farmers in Gujarat, like in most of India, never expected government to curtail supply to the population sector with most influence over politics. In Gujarat, however, farmers were victims to ambitious politicians (with money) that promised reliable power to villages at the expense of agriculture. Instead of claiming to curve power theft and to curtail agricultural power supply (something that would have never succeeded in Gujarat), the Yjotigram scheme, wisely, promised to ‘lighten’ villages and provide reliable power to schools, universities, households, small businesses, and hospitals, all establishments who had felt the intended effects of power theft through voltage fluctuations and outages. If we consider how sales of power to the domestic and commercial consumer classes have increased, how Gujarat has become a surplus power state in recent years, and observe how AT&C losses have decreased in time, we can appreciate the benefits of restructure and Yjotigram with regards to providing a reliable power supply. So, the unintended consequences of power theft in Gujarat were 1) a pragmatic restructure of the state’s electricity board, 2) an unexpected urgency of politicians to act, and 3) an increase in the quality of life everywhere except agriculture.

The accolades for Yjotigram, however, must stop here.[xxxvii] As we have seen, Yjotigram did not address *the* main issue at hand: receding groundwater tables. Recent news reports from Gujarat have suggested that the Yjotigram scheme has done little to bring stability to the receding groundwater tables, and this summer, with 2012 being another year of harsh drought in Gujarat, the state was forced to supply 10 hours of full three-phase power again to farmers.[xxxviii,xxxix] This is a harbinger of things to come, and we go even further to suggest that Ygotigram has made things worse *for agriculture* in Gujarat for two reasons. First, farmers are likely using oversized pumps that have allowed them to irrigate for 8 hours while continuing to draw down the aquifer. Second, agriculture’s sustainability and food security have been jeopardized. Our study suggests that with a fixed supply 8 hours of full power, and at the rate at which groundwater tables are currently receding, farmers will no longer have enough time, and power, to meet the water crop requirement for their fields. In a state where 60% of the agricultural production is comprised of wheat, a staple food in India, the issue of agricultural sustainability and food security is a grave one.

To conclude we highlight that the opportunities for future research in the water-energy nexus are vast. It is imperative for arid, agricultural, developing economies to develop new ways, or adopt existing technologies, to develop resilient energy and water infrastructure systems. There is no doubt that renewable energy will have to play a large role within these more adaptable and resilient systems. Not only do fossil fuels contribute to climate change and ambient localized pollution levels but they compete for water resources in the production of energy. Development agencies must think hard before handing out loans that will inevitably perpetuate a country’s dependence on fossil fuels, and the battle that economic sectors will wage for water and energy.

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