Modeling Rural Electrification in Bihar, India Towards 2030

CCTC 2013 Paper Number 1569695607

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Abstract

Over 400 million citizens in India are without basic access to electricity, the highest percentage live in the state of Bihar. By modeling rural electrification methods, we investigated ways to supply the basic energy needs of the citizens of Bihar. Individual technologies were analysed to determine the change in emissions and costs due to switching from kerosene to solar lanterns, and biomass gasification. Scenarios were developed to estimate state-wide emissions, projected towards 2030, for on-grid and off-grid users. The analysis demonstrated the use of mini-grids can greatly off-set emissions from kerosene, and reduce costs to consumers.

Keywords: rural electrification, energy modeling, micro-hydro, biomass gasification, scenario, solar lanterns, coal

Résumé

Plus de 400 millions de citoyens de l'Inde n'ont pas accès à l'électricité, le pourcentage le plus élevé vivre dans l'état du Bihar. En modélisant des méthodes d'électrification rurale, nous avons étudié les moyens de satisfaire les besoins énergétiques des citoyens de Bihar. Différentes technologies ont été analysées afin de déterminer l'évolution des émissions et les coûts dus au passage du kérosène lanternes solaires, et la gazéification de la biomasse. Les scénarios ont été développés pour estimer les émissions échelle de l'État projetées vers 2030, pour le réseau et hors-réseau aux utilisateurs. L'analyse a démontré l'utilisation de mini-réseaux peuvent grandement compenser les émissions de kérosène, et de réduire les coûts pour les consommateurs.

Mots clés: l'électrification rurale, la modélisation énergétique, micro-hydraulique, la gazéification de la biomasse, le scénario, les lanternes solaires, le charbon

1. Introduction

As an emerging economy India has one of the lowest levels of per capita energy consumption amongst countries of the same economic level, and an overall rate of 66.3% electrification [1]. Rural electrification is a crucial issue facing India. According to recent statistics, 404 million people in India live without electricity, with 380 million living in rural areas [2]. For those households with a connection to the electrical grid, their connection will likely not provide them with full access to electricity. Grid based electricity is unreliable and consistent brown outs leave residents with a very low quality connection [3]. Electricity outages can range from 2-20hrs within a day, and for rural areas it is commonly 14-16hrs a day almost every day of the year [3]. This extensive unreliability means that millions of system users go without electricity for countless hours throughout a given year leading to loss of productivity and substantial disruptions to their daily life.

The State of Bihar is India's poorest state, with a per capita income of RS 17,959, one-third of the national average [4]. The population is primarily rural at 84% in 2008 with only 16% of these rural households have access to electricity while 74% of urban households have access to electricity [5].

In order to substantially change India's current level of development and improve the economic and social situation of the base of the pyramid consumers and population, which suffers most significantly from a lack of access to reliable, a systems-level approach needs to be taken to develop a way to enable them to access affordable energy. Distributed electricity generation, and household energy producing devices are amongst existing viable solutions. This research explores the social, economic and environmental impact that extensive penetration of distributed generation in rural Bihar would have on the state's socio-economic status.

The overall framework of analyses was conducted in three stages to explore distributed generation technologies and how different levels of penetration of these individual technologies in the state of Bihar would impact the socio-economic position of its citizens. First, the micro-scale energy technologies of interest were characterized in terms of cost, life-cycle emissions and methods of distribution. We assessed replacing the predominant source of light, kerosene lamps with solar lanterns, an equally viable and less environmentally harmful alternative. Biomass gasification plants and small scale hydroelectric projects were assessed for rural electrification. Second, the community growth was assessed for current population and estimated population growth for both the rural and urban communities accounting for the migration of rural dwellers to urban centres. Third, a series of scenarios were developed to determine the overall impact on emissions and cost that implementing these micro-scale energy technologies in a micro-grid would have on the province of Bihar compared to a base-case of the current energy generation portfolio. We conclude with the best practices in rural electrification via distributed generation and compares distributed generation to grid based electricity going into the future for Bihar, India.

2. Solar Lanterns

Solar lanterns are a widely marketed alternative to kerosene lanterns which is the primary source of lighting for about 76.9 million rural Indians [6]. The primary objective of the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) electrification program is to provide rural households with basic household use access, primarily lighting and other small appliances, such as rice cookers [7]. Thus, providing lighting using solar lanterns meets a major aspect of a household's requirement. Solar lanterns do not provide the capability to expand capacity towards using large electrical appliances, nor large-scale industrial purposes. However, an analysis of their costs in comparison to kerosene lanterns, and quantifying the CO2 emissions solar lanterns can mitigate as their use becomes more widespread can be useful for policy and planning purposes.

There are many direct benefits from the use of solar lanterns for users, ranging from extended hours to study, safer source of energy without risk of fire, removal of a source of fumes from partial combustion of kerosene, and a brighter source of light about ten times the brightness of broadly used kerosene wick lamps [8,9]. Surveys conducted in hospital burn units have resulted in estimates that about 2% of all burn victims are from kerosene lamps [9].

Removing kerosene lanterns from households can reduce their risk of burns and improve the lighting condition within the household from the increased luminous flux from the solar lanterns.

CO2 emissions from the population of rural Bihar from kerosene lamps are estimated using the most recent available data on the wealth segments of the population, see Figure 1, a set of commonly used kerosene lamps, analysed previously by the Indian Institute of Science, and varying the estimates of the penetration of D.Light solar lanterns (a battery and LED module) until 2030.

In order to estimate the kerosene CO2 emissions from the population of rural Bihar, wealth segments from a recent health survey were used [5]. The wealth segments, see Figure 1, differ drastically between the rural population and the urban population. For this analysis, these wealth segments were assumed to remain at the same percentage throughout the 20 year period from 2010-2030.

According to analysis conducted by TERI, the Life-Cycle emissions from a standard solar lantern are about 7kg of CO2/year [10]. This 7kg of CO2 emissions is far below the average kerosene wick lamp which emits about 80kg of CO2 emissions [11].

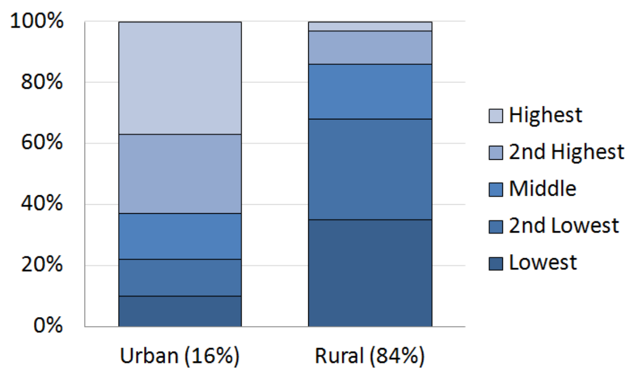

Figure 1. The wealth of households in Bihar. The rural dwellers which represent 84% of the total population are overwhelmingly in the lower wealth quintiles. Figure adapted from [5].

In developing the Base Case, it was assumed that the wealthiest two segments of Bihar's rural population would use two Petromax kerosene lamps which have a higher kerosene efficiency (80ml/hr [11]), and higher luminous flux (1300 lumens [11]) than the conventional wick lamps, but a higher cost. It was also assumed that the middle segment would use one Noorie kerosene lamp, which has a much higher luminous flux (1250 lumens [11]) than a wick lamp, but a lower efficiency than the Petromax and is less costly. The lowest two wealth segments were assumed to use two wick lamps with a kerosene efficiency of 22 ml/hr [11], and luminous flux of 76 lumens [11], as wick lamps are the cheapest light source, and can even be made using a glass jar and a wick. The rural population in 2030 was estimated as having equal growth as the preceding 20 years, and remaining a constant 84% of the total population of Bihar. A steady population growth rate was assumed. This growth in annual CO2 emissions can be seen in Figure 2.

For Case 1 and Case 2, seen in Figure 2, the penetration of D.Light lanterns was extrapolated as a straight line towards 10% and 70% respectively, over the time of interest (2010-2030). The dissemination of the D.Light technology was assumed to take place primarily in the lowest two wealth segments of the population, since this represents the majority of the population, and they would benefit most from a reduced expenditure on kerosene [12].

For Case 3, seen in Figure 2, the penetration of D.Light lanterns was extrapolated as a straight line towards 100%, for use in all of the segments. This is an extreme case, since as the communities transition from kerosene, to solar lanterns, it is likely that they will move towards other distributed or centralized power sources (if they were to become available) to provide for higher consuming electricity appliances such as irrigation equipment for agriculture, or industrial uses, such as powering a manufacturing plant or grain mill.

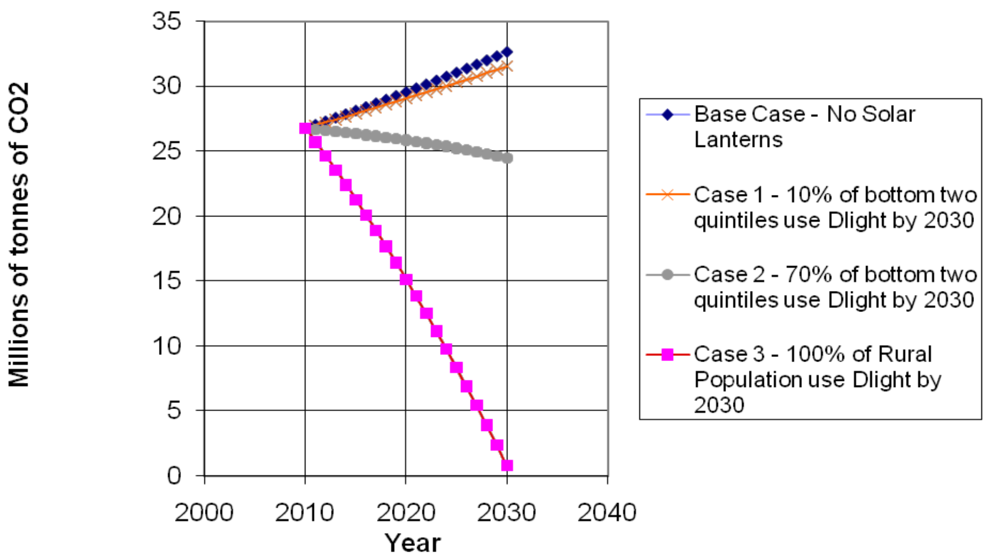

Figure 2. CO_2 emissions from lighting sources in Bihar. Projections for Solar Lantern Use in Bihar between 2010 to 2030.

3. Biomass Gasification

Biomass gasification for power production has been used throughout India for a number of decades. A biomass gasifier takes solid biomass as its input and converts it into a combustible “producer gas” also known as a synthesis gas or syngas. This producer gas tends to have a low thermal value, ranging from 1000-1100 kcal/m^3, containing CO, H_2, methane, lighter hydrocarbons, H_2O, nitrogen and trace amounts of tar, alkali vapors, sulfur compounds[13][14]. The process requires drying of the biomass to lower the high moisture content, followed by pyrolisis, oxidation/combustion and reduction, which produces the producer gas and a solid waste of ash and fixed carbon. Pyrolisis is the chemical decomposition of organic material by heat in an oxygen-starved environment [15]. The producer gas is subsequently filtered, treated and scrubbed prior to combustion in a standard engine-generator.

The organic material can be sourced from a variety of agricultural and forestry related industries. Studies have been conducted on the producer gas from standard wood, pine needles, branches, green wood, saw dust to agricultural wastes such as coconut shells, rice husks, cotton residues [16]. The composition of the producer gas is dependent on the organic material. Some of the advantages of this technology include local sourcing of fuel, CO2 emissions can be discounted, since the organic material is considered as land-use change in

GHG accounting, significant amounts of electricity can be produced upwards of 35kW for a small scale plant[17][18].

Husk Power Systems (HPS) is a social enterprise that works in rural Bihar providing villagers with electricity from biomass gasification from rice husks. Fuel costs are on the order of $260USD per month, and the plants consume about 50kg/hr of rice husks[19]. To minimize costs, they rely on manual labour to clean and scrub the system, running each plant for 6-8 hours per day typically after sunset and leaving the remaining hours for cleaning, processing the fuel and maintaining the system[19]. Villagers are charged prior to electricity use based on the number and type of light bulbs in their residence, most consumers are provided with a single 30W CFL, or two 15W CFL plus unlimited cell-phone charging for 80-100 Rupies (Rs) per month [20].

Following a similar procedure, as that which was conducted for comparing kerosene lanterns to solar LED lanterns, the CO2 emissions and costs were estimated for the state of Bihar. In conducting a survey of the literature on life cycle assessment of biomass gasifiers, it was determined that due to the long life of the systems, the CO2 emissions from the manufacture of the gasifier systems and the equipment could be considered negligible[21]. Similarly, the CO2 emissions from the combustion of the syngas derived from biomass is considered carbon neutral, since CO2 from biomass is considered as greenhouse gas neutral[21]. Transportation of the biomass fuel would have significant effects on global warming potential if the distances were large, however since the biomass is sourced locally these emissions can also be considered as negligible [21].

Lighting is the primary use of the electricity provided by small-scale rice husk biomass gasifiers, such as those employed by Husk Power Systems. It is for this reason that the CO2 emissions were quantified for the base case if all villagers use kerosene lighting. Husk Power Systems has projected that they will have 500 fully operational plants by 2014 [19]. A linear growth rate was assumed for Husk Power systems, a straight line extrapolation was done for the years 2015-2030. Assuming that Husk Power Systems can maintain a consistent level of growth is a conservative estimate, since with their business model moving towards franchising, it is probable that instead of a linear rate, they will increase the use of their technology exponentially. There are also concerns that after all of the best-suited villages have been electrified there will be a tapering off of plant installations, since the costs will increase as the sites will be harder to implement the biomass gasification. Quantifying these speculations is not possible hence they have not been inputted into the model.

Consumers of Husk Power Systems (HPS) stop using kerosene since the electricity provided is sufficient, reliable and effective at meeting their lighting and cell-phone charging needs. Inputting this into the model revealed savings of between about 5400 tons of CO2/year to about 280 000 tons of CO2/year, as can be seen in Figure 3. The third line in Figure 3 compares the use of Biomass Gasification to conventional generation through diesel powered generation of equivalent size.

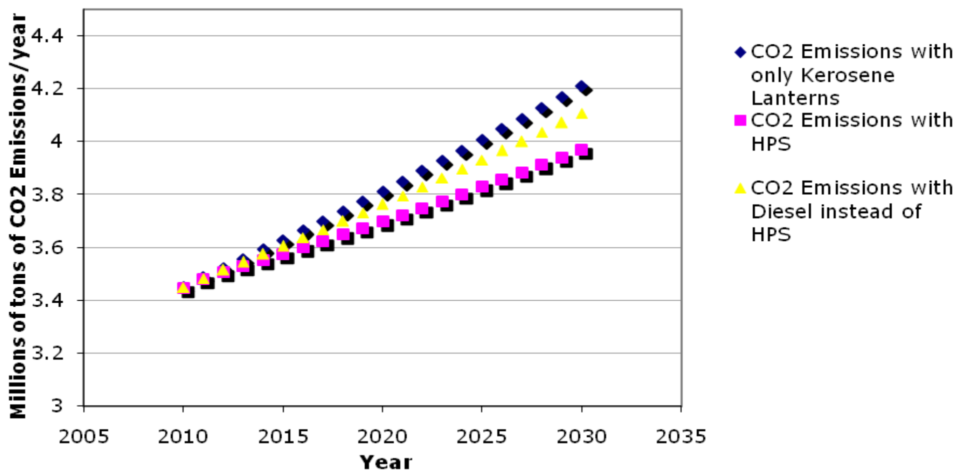

Figure 3. Estimated CO_2 Emissions from Lighting Requirements for Rural Bihar

The cost savings for rural Bihar were estimated considering only the replacement of fuel costs for kerosene lighting. As in section 2. Solar Lanterns, the wealth segment percentages were used. The population's baseline use of kerosene was estimated based on their wealth, and ability to pay for higher quality lanterns which also tend to consume more fuel per hour. The population was divided into three portions, the top two wealth segments using two Petromax lanterns for four hours per day, the middle wealth segment using one Petromax lantern and one Noorie lantern for four hours per day, and the third portion, consisting of the bottom two wealth segments, using two low quality wick lamps. The three wealth portions with the corresponding kerosene fuel consumption per year and cost to individual households for fuel per year. As HPS increases the number of operating plants, individual households will be able to reduce their monthly expenditure on lighting by 56%-89%, see Figure 4.

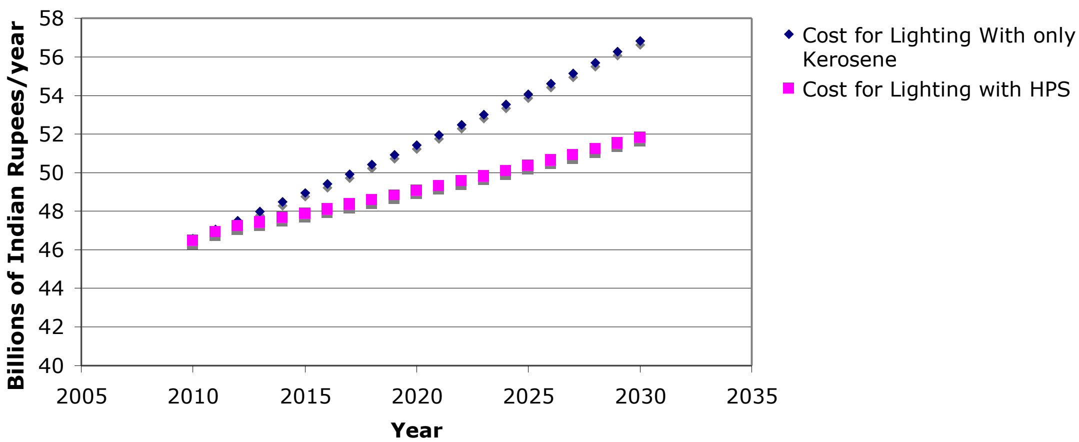

Figure 4. . Estimated Summed Cost Savings for the Rural Population of Bihar when lighting is produced using HPS compared to Kerosene

The introduction of a biomass gasification plant into a community has significant quantifiable and unquantifiable benefits. CO2 emissions from kerosene lighting along can be reduced by about 5400 tons of CO2/year to about 280 000 tons of CO2/year by 2030. Individual households can reduce their monthly expenditure on kerosene fuel from between 180Rs-670Rs to a clean source of electricity at only 80Rs/month.

4. Scenario Design and Analysis

In developing the following four future scenarios, the analysis conducted in the preceding chapters was built upon and extended to include not only the rural population of Bihar, but also the urban population. As well, rural to urban migration was taken into account in these scenarios using, in part, estimates from the India Urbanization Econometric Model created by McKinsey Global Institute Analysis [22].

The overall method was to design a number of scenarios which would demonstrate the environmental justification as well as the economic justification for supporting rural electrification and low carbon emitting technologies. Since all of these scenarios are mere estimates about what could occur in the future, none of the data points have error-bars or regression analysis associated with them. In developing the various scenarios, inspiration and guidance was wrought from the Intergovernmental Panel on Climate Change, as well as literature on scenarios and scenario planning[23][24].

The time frame for this analysis is 2010 to 2030. The geographic location is the state of Bihar, India. The major stakeholders are the residents of Bihar, the government of the state of Bihar, the Indian Government, Private electricity providers, major NGOs that work in the region, for example, Greenpeace Bihar, and international financing organizations, such as the World Bank and the IMF. There are many other stakeholders who could be included such as village-level NGOs. However, as a first analysis these are the major stakeholders considered in designing the suite of scenarios. The major trends that will be considered are the carbon intensity of different electricity generation technologies, urbanization, population growth, GDP growth as a proxy for increasing energy use, and the penetration of renewable and low-emission electricity generation technologies.

The carbon intensity of the grid based electricity was determined by adjusting the national carbon intensity of the grid for the state of Bihar which does not have nuclear, and has an increased percentage of coal based electricity [25].

Urbanization will be dependent on economic growth [22]. Since Bihar is currently the poorest state in India, and has the largest percentage with a rural population, this is expected to remain consistent into the future. By 2030, Bihar is anticipated to have an urban population of 21.3 Million, representing 17% of the total population in Bihar [22]. This economic model was developed using data from 2008, given that Bihar currently has an urban population of about 17%, it is reasonable to assume that this will only grow over the next 30 years since Bihar was able to achieve a doubling in the percentage of their urban communities in only two years [22]. These annual growth rates were used for the time-period 2010-2030 to more closely characterize the movement of individuals in Bihar from a predominantly rural community into a more urban based state.

According to UN estimates in 2009, the population of India is expected to grow to 1.48 Billion people by 2030 [26]. The population in Bihar was projected to grow to 183 Million by using the UN's projected annual growth rates in both the urban and rural populations within India in combination with Bihar's current urban and rural population sizes.

The business as usual (BAU) scenario, serves as a baseline of possible emissions. It starts with the 2010 point described above. The 2030 point is an estimate based on the current energy trends of Bihar. The Carbon Intensive Mix (CIG) represents if Bihar's power comes from 97% from coal and 3% from hydro electric power. Per annum, the CO2 emissions were calculated to be 8.8million tonnes of CO2 in 2010 when 8895GWh of power were used.

In developing the learning scenarios the initial starting point in 2010 was made consistent across scenarios. The population was divided into rural and urban using the urban-rural proportions from throughout the analysis in this thesis, 16% urban and 84% rural population [16]. The urban population was then divided into on-grid (74%) and off-grid(26%)[16]. The rural population was then divided into on-grid (16%), mini-grid (using the number of HPS and hydro-electric customers estimated in the preceding chapters in 2010, 0.2% of the rural population was estimated to be on a mini-grid), off-grid(83.8%).

The energy usage in each of these groups was matched with their status of on-grid, off-grid or mini-grid. In the case of on-grid, the CO2 intensity of the grid was estimated using information on Bihar's energy supplies.

This set of scenarios is variations using the same Carbon Intensive Grid, as is used in the BAU scenario. The CIG output of CO2 emissions was estimated using the kg of CO2-eq/kWh from [26]. The largest emissions were calculated to occur with all consumers on the grid, "2030-CIG-All-2" in Figure 23, receiving around 1500kWh per capita. The scenarios with "All-2" in their name are examples of how much the CO2 emissions would increase if the citizens of Bihar had access to similar or equal energy usage rates as the rest of India. In "2030-CIG-All-1" the total GWh estimated for 2030, are simply distributed between the rural population and the urban population, leading to about 400kWh per capita, which is well below the average for Indians in 2010 at about 800kWh [21]. These "All" scenarios simply serve to show that if all of Bihar were to move to electrical grid, the CO2 emissions are highly dependent on the fuels for the electrical grid power generation and the per capita usage of energy.

The scenario named "2030-CIG-MG" puts the majority of the rural population on mini-grids. Instead of only using biomass and hydro-electric, the villages are assumed to install small-scale solar and small scale wind where possible. The number of residents using electricity from a mini-grid was calculated by taking the total rural population in 2030 minus 16% of the rural population using grid based electricity and 20% of the rural population using D.Lights. The Mini-grid population that uses solar and wind is assumed to use 200kWh, which is well below the Indian average, but almost double the current per capita consumption in Bihar. These assumptions about the amount of per capita kWh was made to enable estimating the emissions from village-level wind and solar, instead of not counting any emissions. The on-grid population, both rural and urban, was assumed to use about 1500kWh, (GDP growth based total power) from the Carbon-Intensive grid. The urban off-grid population was assumed to use D.Lights.

The scenario named "2030-CIG-Ker" is similar to the BAU scenario. The only difference is that all off-grid population continues using kerosene. None of the population is estimated to use D.Lights in this scenario.

The carbon emissions of each of the scenarios is found in Figure 5

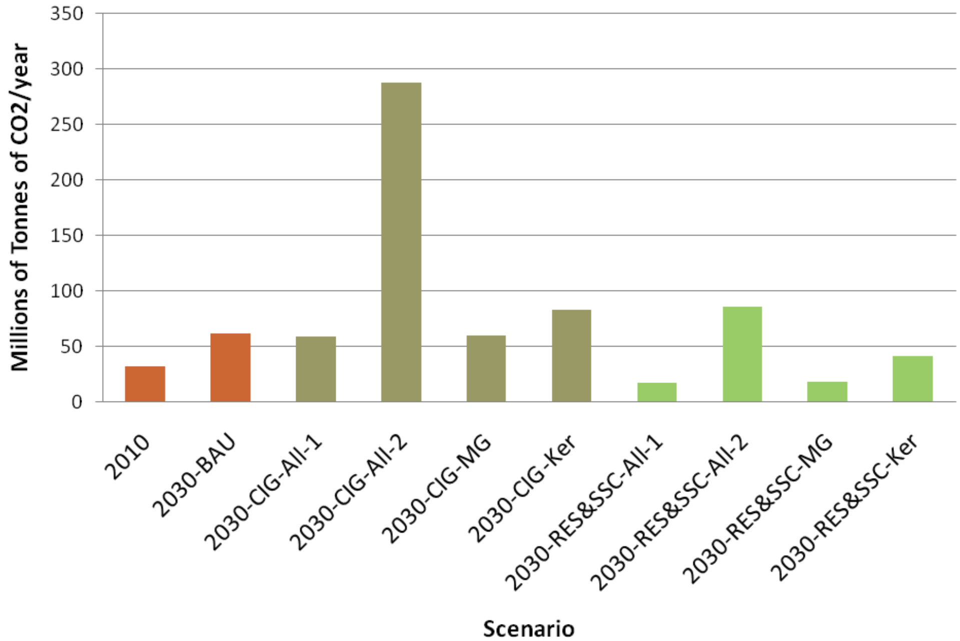

Figure 5. Carbon dioxide equivalent emissions for the scenarios between 2010 to 2030 for Bihar.

To determine the impact the different groups of users, rural vs. Urban and on-grid versus off-grid contribute to the overall emissions, the $CO_{2\text{-eq}}$ emissions can be broken into sector, see Figure 6.

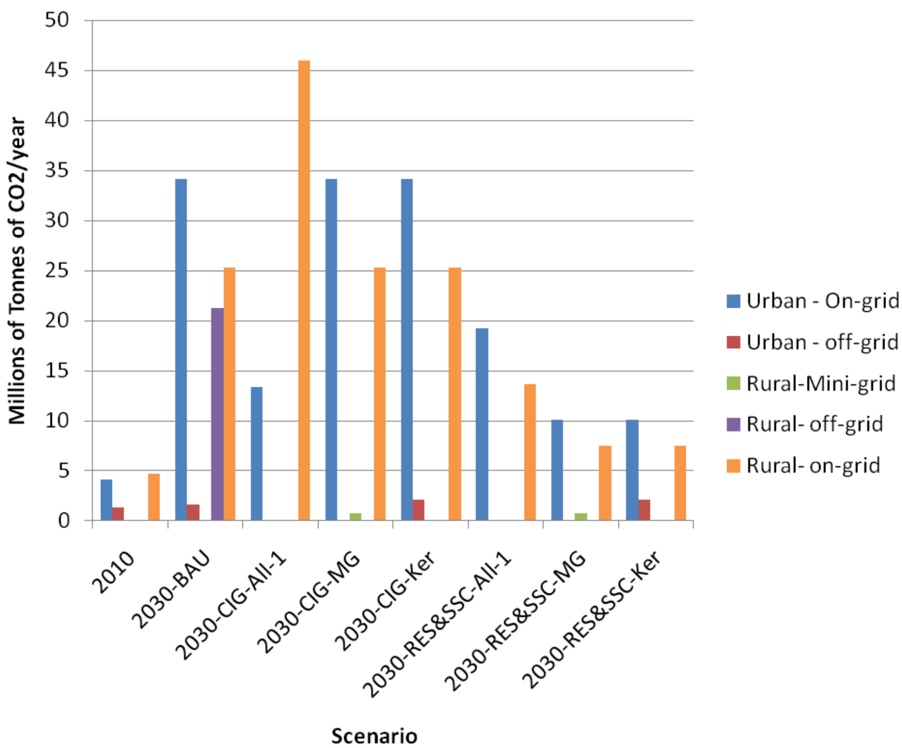

Figure 6. CO_2 Emissions from selected scenarios divided into emissions from on-grid and off-grid users

5. Conclusion

In conducting these scenarios, it aids in visualizing and quantifying the impacts of policy decisions on rural electrification. Some common threads and themes become evident. Although many of the industrialized nations have followed a development scheme where all consumers became connected to a large state grid, this is not necessarily feasible, cost-effective, nor environmentally responsible in some geographic regions such as Bihar. The environmental costs of mass grid-based electrification to achieve useful levels of consumption per capita would result in emissions well above current levels. Alternate means of electrification using mini-grids and personal lighting devices, such as D.Light solar lanterns can alleviate the carbon emissions related to kerosene lanterns, and support an increase in electricity consumption for agricultural, industrial and household use. Future studies could include conducting similar scenario based analyses for other regions and communities lacking basic access to electricity.

Costs for scenarios could be estimated in order to give government stakeholders a sense of levels of required subsidies to promote certain technologies, such as distributed generation, solar, wind, biomass gasification and small and micro-hydro. These cost and subsidy estimates could be grounded in economic analysis, GDP growth estimates, among others.

The technologies selected in this analysis were chosen based on their breadth, viability, proven utility and distinctiveness from one-another. Expanding the work to include analyses of geothermal, village-level wind, village-level solar and solar home systems would provide a more complete picture of rural electrification for inclusion in scenarios.

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7. Acknowledgements

The present work was supported by Carbon Management Canada, a federal Network of Centres of Excellence. The authors would like to thank the Prayas Energy Group from Pune, India. The authors would like to acknowledge the guiding hand of the Centre of Global Engineering and the Thermofluids for Energy and Advanced Materials Laboratory at the University of Toronto for their collective assistance and encouragement.

8. Biography

M. Freire-Gormaly is a graduate from the University of Toronto with a B.A.Sc. in Engineering Science with a major in Energy systems, and a current graduate student in Mechanical Engineering. M. Freire-Gormaly has a keen interest in sustainability and reducing the impact of energy generation while meeting the needs of all those in society.