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# Exploring the impact of increased solar deployment levels on residential electricity bills in India

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## Abstract

In this study, we explored how increased solar penetration in the electricity generation mix may impact residential electricity consumer bills. The study is divided into two sections: simulation of wholesale electricity rates and retail rate modeling. In the first stage, wholesale prices were modeled for different energy mix scenarios based on the increasing level of solar penetration, ranging from 5 to 40% on energy basis. The wholesale electricity prices were modeled using a bottom-up long term unit commitment optimization model. The simulations indicated a fall in wholesale prices with increased solar penetration, a result of the merit order effect. The simulated wholesale prices were then used to model retail rates for residential consumers. Four different types of retail rates were designed: flat rate, real time pricing, time of use and critical peak pricing. We analyzed the impact of these retail rate mechanisms on electricity bills of residential consumers, and found that the bill savings achieved from time varying rates are greater than for time invariant rates. With increased solar penetration, customers with time varying rates are likely to benefit the most from electricity bill savings. Although consumers with the flat rate are also likely to benefit from bill savings, the savings are likely to be lower than with time-varying rates.

**Keywords**: Energy System Modelling, retail electricity rate design, Indian electricity market, grid integrated solar, Indian energy policy

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**Abbreviations:**

AMI-Automated Metering Infrastructure

CAGR- Compound Annual Growth Rate

CPP- Critical Peak Pricing

DCU-Data Concentrator Unit

DSM- Demand Side Management

GOI-Government of India

IEX-Indian Energy Exchange

INDC -Intended Nationally Determined Contribution

JERC- Joint Electricity Regulatory Commission

KEB- Karnataka Electricity Board

KPTCL- Karnataka Power Transmission Corporation Ltd

LT-Low Tension

PAT- Perform Achieve and Trade

PV-Photovoltaic

PX-Power Exchange

RE-Renewable Energy

RES- Renewable Energy Sources

REC-Renewable Energy Certificates

RGGVY- Rajiv Gandhi Grameen Vidyut Yojna

RPO- Renewable Purchase Obligation

RTP-Real Time Pricing

TOU- Time of Use

# 1. Introduction

The Government of India (GOI) aims to integrate 175 GW of renewable energy in the grid by 2022, which includes 100 GW of solar, 60 GW of wind energy and 15 GW of biomass other than small hydro [1]. In order to achieve this aggressive renewables target, appropriate regulatory and policy frameworks will need to be developed and implemented. The GOI has ensued a two pronged approach to meet the maximum demand with minimum carbon emissions. There are a number of examples to learn from, as many countries have adopted policies to promote greater use of renewables in the generation mix and more efficient use of electricity through demand side management [2-5]. Integrating renewable energy sources (RES) in the grid will require increased usage of ancillary services, including spinning and non-spinning reserves, regulation up and down, continuous ramping, as well as load following strategies [2]. The integration of various policy platforms wherein energy efficiency, climate change and Demand Response (DR) are considered is critical for the success of DSM [4]. Various reasons like complexity of the system operation, dearth of metering, communication and information infrastructure, inadequate understanding about benefits of DSM as well its competitiveness with existing approaches, hinder the implementation of DSM [5].

The average annual per capita electricity consumption in India is 957 KWh, corresponding to about 7.4% of per capita consumption in the United States [6, 7]. However, expected population and economic growth could lead to a dramatic increase in electricity demand. To ensure long term environmental and social sustainability, the model of growth for India will need to be equitable and inclusive, while minimizing environmental and health impacts of electricity generation.

Various strategies and polices have been developed to ensure that target energy requirements are met in a sustainable manner. The National Electricity Policy and Integrated Energy Policy emphasizes universal energy access as well as integration of renewables. The Energy Conservation Act focuses on encouraging energy efficiency through establishing standards for appliances, prescribing norms and standards for energy consumption, and certification of equipment. Other policies, such as fiscal instruments (e.g. reduction in electricity subsidies, increased taxes on coal and fossil fuels), market mechanisms (e.g. Perform Achieve and Trade (PAT), Renewable Energy Certificates (REC)) and regulatory regimes (e.g. Renewable Purchase Obligation (RPO)), are devised to support sustainable and clean development [1].

There has been a rapid growth in solar installation in India in the recent years. From a modest capacity of 37 MW in 2010, total installed capacity has increased to over 9 GW in 2016, with a 74% year-on-year growth in capacity in 2016 [8]. India ranks 7th globally in terms of installed solar capacity [8] and trails behind the countries with the highest installed solar capacity, which include China with a total capacity of 77.8 GW, Japan with 41.6 GW, and Germany with 41.0 GW in 2016 [8]. Tamil Nadu, Gujarat, Karnataka and Rajasthan are the states with highest PV capacity in India [9]. To promote rooftop solar PV in India, most states have enacted policies (net metering[2] and feed-in tariffs[3]) to support grid integrated PV [10].

As coal constitutes of over 60% of the electricity energy mix in India and is expected to remain a dominant source for electricity generation in the near future, various measures have been undertaken by government of India to improve the efficiency of electricity generation from coal to reduce its carbon footprint. Coal power plants are now mandated to use supercritical steam generators and coal beneficiation, in addition to other emission measures to reduce greenhouse gas emissions. The coal tax has quadrupled to Rs.200 per ton, which has improved the relative economics of clean energy projects [1]. India has conceptualized its Intended Nationally Determined Contribution (INDC) in response to the United Nations Framework Convention on Climate Change Conference of Parties decisions 1/CP.19 and 1/CP.20 for the period 2021 to 2030. Policies have also been proposed to increase non fossil fuel based electricity generation to 40% of cumulative installed capacity by 2030 by making low cost international finance (such as the Green Climate Fund) available to developers and by facilitating technology transfer from industrialized countries. Independently from the various initiatives taken by the government of India to reduce usage of coal, fossil fuel based sources of energy alone are not able to support the growing demand of energy. Hence, India is turning to solar energy to serve the increasing

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[2] Net metering allows consumers to get compensation for the amount of energy they send back to the grid

[3] Feed in tariff compensates for all the PV units generated by a consumer

demand for energy as well as to serve unelectrified portions of the population, due to its generous solar resources as well as its potential to mitigate climate change.

The higher solar energy penetration and developments of smart grids proposed by the GOI would lead to a change in the structure and dispatch of the power system, and hence a change in electricity markets and energy economics [58,59]. In this study, we examined the implication of increased solar penetration on the economics of residential consumer. The study is divided in two parts: simulation of wholesale electricity rates and retail rate modeling. The restructuring of the electricity market in India as well as an increased participation in the wholesale electricity market would augment the DSM policies.

This research aims to unravel the connections between retail rates and increased renewable penetration, using Karnataka as a case study. It is the first known effort to understand and quantify the connections between wholesale market conditions, retail rates, and the value to residential customers in India, contributing to the literature on renewable support policies and initiatives in India.

### 1.1. Literature review

Various types of energy system models have been developed to study future scenarios which assist stakeholders and decision makers in industry and policy design.

There are two fundamental modeling approaches for energy system models: top-down and bottom-up. Top-down models generally assess the system in an aggregated form and focus on the macro-economic perspective with a typical formulation in a general equilibrium form. These models are characterized by rules of substitution between different resources and sectors rather than a technology specific description of the system. Notable examples of top-down models include the WITCH [11] and ReMIND [12] models. Their formulation guarantees a global optimum often reflecting a best case scenario which can serve as a reference point for policies. However, this generality requires a more coarse representation of technology, temporal and spatial resolutions. Bottom-up models, on the other hand, explicitly model technology specific substitutions. Since the focus of these models generally lies on the detailed representation of a single market of the economic system, this approach is characterized by technology rich modeling often formulated as a partial equilibrium model, leaving out inter-sectorial effects. Notable examples of bottom-up models include TIMES [13], MESSAGE [14] and OSeMOSYS [15]. Generally, the strength and weaknesses of these bottom-up models are antagonal, as more detailed system representations come at the cost of a loss of generality.

The research objective in the paper requires a detailed bottom-up technology specific unit commitment model, to be able to accurately model wholesale price of electricity at the required spatial and temporal resolutionVarious examples of models exist with a detailed representation of the wholesale market for electricity, such as the REMIX [16] and Dispa-SET [17]. However, the peer-reviewed literature lacks detailed bottom-up modeling studies of the Indian electricity market. To fill this apparent gap in the literature, we apply the German Energy System Optimization (GESOP) [18] model to the Indian market which forecasts electricity exchange prices for higher penetration of renewable energy through scenario analysis.

Wholesale electricity price models can be designed to optimize various objectives. Optimization of marginal cost to achieve wholesale prices is one of the most common techniques in energy systems models.

Owing to almost zero marginal costs of RES, the increased renewable penetration in the energy mix impacts the wholesale electricity prices. In a study of Italian power market, it was found that an increase of 1 GWh in the hourly average daily production from solar and wind led to a 2.5$/MW and 4.7$/MW reduction in wholesale price, on average, over the period of 2005-2013 [19]. In the case of Germany, renewable energy sources were found to be responsible for a decrease in market prices, leading to a 30 billion euros savings for German power consumers in 2011 and 2013, compared to scenarios without renewables [20]. In another analysis of the Australian national electricity market, increased PV led to the reduction of wholesale prices [21]. In the Dutch electricity market, it was found that increasing RES impacts the wholesale electricity prices [22]. Wind to the Irish electricity market dispatch led to a 12% reduction in the total costs to the market and savings of €141 million to the market dispatch [56]. In the state of Illinois, in the United States, simulation analysese showed that the average electricity prices reduced with increasing wind penetration [57].

Though there are a number of models to predict marginal electricity costs as a result of increasing renewable penetration rates, models that map wholesale prices to retail rates are rare. It is anticipated that, increasing renewables and liberalization of market will prove to be critical in determining the electricity rates [23]. Darghouth et al. (2014) developed a methodology to design retail rates from wholesale prices for net metered consumers [24]. In this analysis, it was found that PV compensation mechanisms along with retail rates can greatly impact the value of bill savings for consumers. In another report by Darghouth et al., value of bill savings were calculated for 226 consumers of California. In this study, the impact of time varying and non-time varying rates was studied under different scenarios of renewable penetration [25].

### 1.2. Electricity market in India

In spite of significant growth in installed capacity in India in the past decade, supply has consistently lagged behind demand. In the 1990s, large energy and peak capacity deficits, and the resulting rotational load shedding, led to the development of competitive electricity markets which aimed at addressing these issues. With the enactment of the Electricity Act of 2003, regulatory changes led to delicensing generation and provided impetus to the formation of a market with multiple buyers and sellers, which was further strengthened by open access regulation in 2008.  The positive regulatory moves led to the creation of a vibrant electricity market with the rapid development of generation capacity, benefiting suppliers, consumers and the sector as a whole.

There are two power exchanges in India, namely the Indian Energy Exchange (IEX) and the Power Exchange India Limited which operate intraday, daily, and weekly markets. The power exchanges operate day ahead market on a 15 min interval trading and term ahead market on daily or weekly basis. There are 5 sub regions in India geographically as shown in figure, 1 with 12 zones. There are two sub grids: the North- East-West-North East (N.E.W) Grid and the South Grid which are inter connected asynchronously [26]. Although relatively small amount of electricity being traded over power exchanges, a transparent and efficient price evaluating mechanism had proved to be important in setting prices for long term contracts [27]. The power exchanges also help in specifying the location and type of new capacity required in the market. The improvements in liquidity and efficiency of market can be observed in the reduction of the number of price peaks and volatility.

The formation of power markets has led to the optimization of power purchase portfolios of utilities and hence reduced overall power purchase costs. Almost 80% of the average tariff of the ultimate consumer is formed by power purchase cost [26]. Whereas the base load power requirement is often met through long term purchase power agreements (PPAs), the intermediate load is met through medium and short term bilateral contracts. The power exchanges are utilized to meet peak load and seasonally varying load requirements [26].

The power exchanges have facilitated in reducing the demand supply gap by providing an auction mechanism with low transaction costs and hence improving the grid reliability. This is critical in such a price sensitive market, where utilities opt for load shedding rather than buying expensive power through a protracted administrative process. It was found that, if the amount of power which is shed is procured through the power exchange, the total cost to the distribution utilities would be far less than the societal cost of not serving the energy [26].

The Indian electricity markets have not yet realized their full potential. The power exchange accounts for 29% of electricity of short term market as per the report of Indian energy exchange (IEX). It is estimated that 15% of the power from new capacities will be purchased outside long term PPAs, traded on power exchanges. A report by AF Mercados signals a potential of 15% of buying capacity across states in India. But the potential is estimated to be 23% if load shedding was 10%, as indicated in a market report of power exchanges. This potential is expected to increase further if the large industrial consumers are allowed to buy power from short term markets. The price signals close to variable cost of generation of power plants is an implication of the merit order effect and indicates efficiency of market. [26]

The need of ancillary services market to cater to power generated from renewable energy (RE) will lead to a reinvigoration of the intraday market, where power exchanges would play a crucial role. The reduction in prices would also lead to a requirement of policy intervention for capacity investment. In turn, this would instigate the formation of capacity markets in order to meet the need for peaking power plants in India. The short term transactions (OTC and power exchange (PX)) form 9% of total generation in India [28]. However the CAGR shows a growth of 22% in last 5 years. The maximum amount of electricity traded is day ahead which constitutes 97% of total volumes traded on PX [27]. Apart from utilities, retail consumers, large IPPs and captive generators also participate in the market.

Distribution companies, or discoms, have been able to design an optimal mix of long term and short term contracts for hedging against risk. For a certain volume of electricity, the discoms are able to replace expensive long term PPAs with less expensive power available on PX. The states participating actively on exchange are Tamil Nadu, Punjab, Andhra Pradesh, Rajasthan, Gujarat and Haryana, which have large number open access industrial consumers. The open access consumers trade almost 6-7 BU of power [26].

The CAGR installed capacity is 10% for 2015-16. The share of state decreased from 56% to 34%, center sector from 32% to 25% and that of private sector increased from 13% to 41% during the period 2006-078 to 2015-16. The average cost of supply increased from Rs. 3.4/kwh 2008-09 to Rs. 5.15/kwh in 2013-14 [28].

**Figure 1: Regional zones in power exchange in India**

The amount of power traded on PX was 115.23 TWh in 2015-16, 16% more than previous year. The total volume of electricity traded on short term market by discoms increased from 9% to 21% in 2015-16.

# 2. Material and Methods

## 2.1. Case Study: Karnataka

Karnataka is a state in south India (in the S1 power exchange zone). As per the report of Joint Electricity Regulatory Commission (JERC) regarding the status of electricity scenario in Karnataka, the state reports 4% electricity deficit. The state, on an average, provides 22 hourshours daily of electricity to domestic consumers in urban areas and and 16-18 hours daily in rural areas [29]. The average daily consumption of an urban consumer is 3.00 kWh and is expected to increase to 4.35 kWh by 2019. The average daily consumption of a rural consumer is significantly lower, at 1.19 kWh [30].

It is projected that the share of industrial consumers will decrease and the share of domestic consumers in the demand will increase from 25% to 30% of the total electricity consumption in the state [30]. The total installed capacity in Karnataka is 15 GW, which includes the central generating stations [31].

Karnataka is the first state in India to have formed separate entities for generation and distribution of power. When first formed, Karnataka Power Corporation Ltd. (KPCL) overlooked generation of power while Karnataka Electricity Board (KEB) owned transmission and distribution rights of the power. In 1999, KEB merged with Karnataka Power Transmission Corporation Ltd. (KPTCL). KPTCL was further disintegrated into a transmission company and four distribution companies: Bengaluru Electricity Supply Company Ltd. (BESCOM), Mangalore Electricity Supply Company Ltd. (MESCOM), Hubli Electricity Supply Company Ltd. (HESCOM) and Gulbarga Electricity Supply Company Ltd. (GESCOM) in 2002 and Chamundeshwari Electricity Supply Corporation (CESC) in 2005 [29]. Karnataka Electricity Regulatory Commission (KERC) was formed as an autonomous body to regulate all the matters related to power in the state. The energy mix of Karnataka indicates that only 1% of electricity is generated from solar, as observed from figure 2.

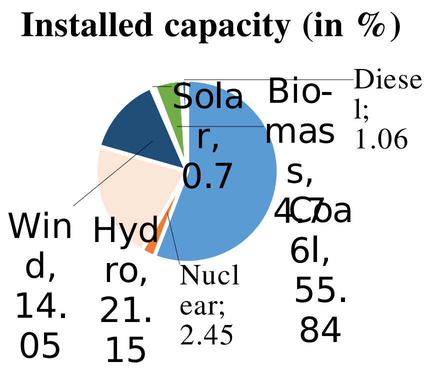


**Figure 2: Installed capacity in Karnataka (author's analysis from sources [29,32,33]**

## 2.2. Data

The data used for the analysis are freely available from state load dispatch centers, websites of various utilities, and open source models. The list of power plants used for the input includes state generating facilities, as well as central generating facilities and power plants from other states that export to Karnataka. Generator characteristics, such as number of blocks, size of blocks [29,32,33], year of commissioning [33,34], availability factor [35], fuel cost of generation [36,37], variable cost [38], fuel tax [1], lifetime and generation efficiency [39,40] were used as inputs to the wholesale price model.

The fuel cost of generation for renewable energy sources was assumed to be zero. The variable cost of generation for all the sources of power generation are based on US data from the US Energy Information Agency (EIA) [38]. The variable cost of generation includes the operation and maintenance costs and other miscellaneous costs.

We used generation efficiency of power plants data from a report by Gatzen 2008 [39] and Schröder et al. 2013 [40] for plants from 2012 onwards . Foryears prior to 2012, we used data from Ellersdorfer [41] 2009, asolder generators tend to have lower efficiency levels. Variable costs of generation were directly calculated from generator efficiency and fuel costs.

The times when the plant are online and available to generate power determines the availability factor. The availability factors used are from VGB PowerTech 2010, the European technical association for power and heat generation [35]. The technical lifetime for different types of power plant are from Schröder et al. 2013. The solar generation profile was simulated using PVWatts [42] with solar resource data for Karnataka, and the aggregate wind generation profile was simulated using a model described in [43]. The hydro generation profile data was compiled from load profile data available on the Karnataka load dispatch center website [44].

### 2.2.1. Solar profile

The PV generation profile used for the simulation is plotted in figure 3. The solar generation starts as early as 7:00 in the morning and falls back to zero at around 18:00 hours in the evening (figure 3b). The average solar radiation in Karnataka is 5.4 to 6.2 kWh/m$^2$/day [46].

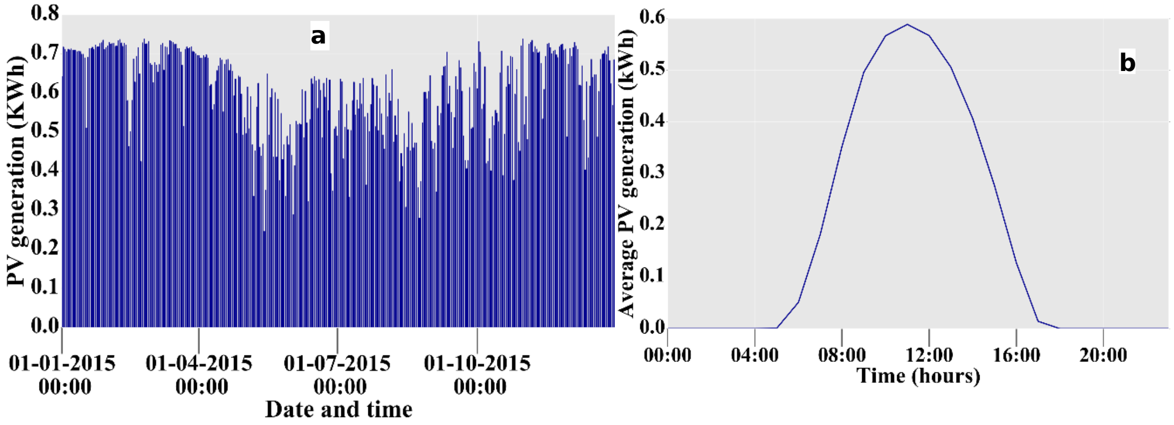


**Figure 3: a) Annual hourly solar profile and b) Average daily solar profile of Karnataka for a 1 kW system**

### 2.2.2. Karnataka's load profile

The aggregate hourly load profile for Karnataka in 2015 was used as inputs to our simulations [44]. The average hourly consumption over a year is shown in the figure 4b. Missing values were replaced with data from the previous day belonging to same hour. As can be observed in Figure 4b, there are two peaks in the load curve, one in the morning (8:00 to 9:00) and another in the evening (19:00 to 20:00). The maximum and minimum hourly consumption for 2015 was 9549 MW and 3615 MW on March 26 at 11:00 and June 1 at 02:00, respectively. The average consumption is 6981 MW. The month with the highest total load is March, whereas the month with lowest load is September. The maximum load is during summer months (March-June) and lowest during monsoon (July-October).

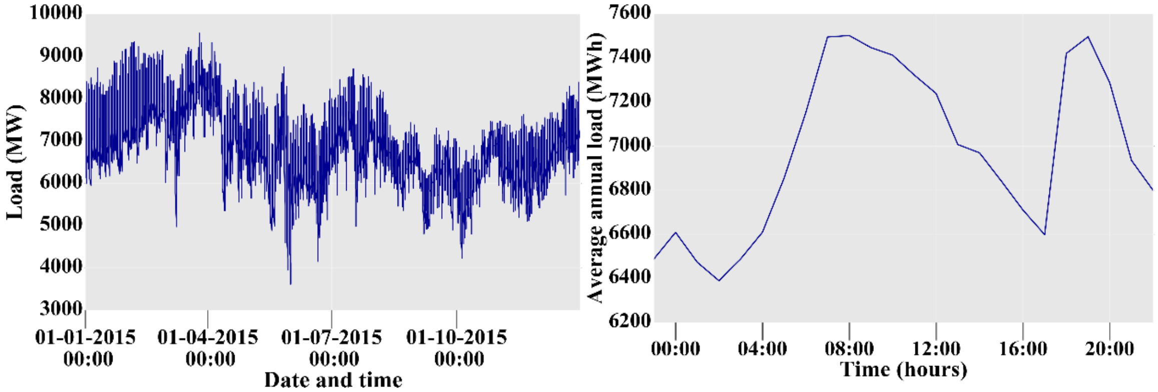


**Figure *4*: a) Total demand of the state during 2015 and b) Average daily demand profile**

### 2.2.3. Consumer load profile

The consumer load data used in this analysis was collected using 75 single phase and 22 three phase residential meters, over a one-year period beginning on July 1, 2013. The data was collected from consumers residing in the semi urban areas. The meters were installed in the homes of domestic consumers as a part of a smart grid pilot project in Puducherry, India [45]. The smart meters sent hourly load data in real time to the data concentrator unit (DCU) where it was aggregated and sent to the main server system. When data was found to be missing during the preprocessing phase, an average value of consumption preceding and succeeding time intervals was used [45]. Figure 5 shows annual average consumption of a residential consumer.

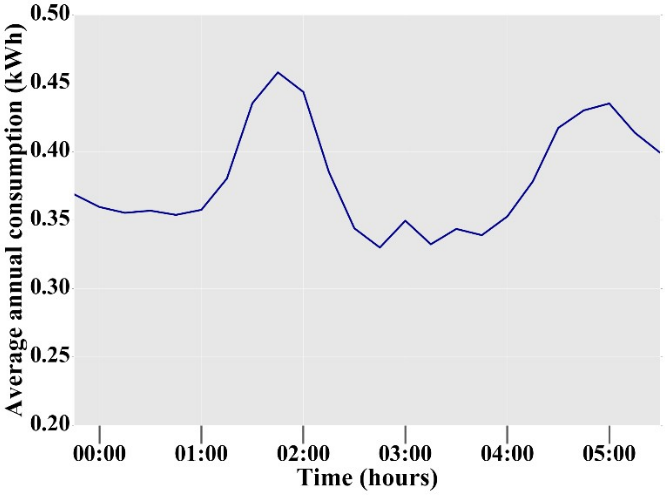


**Figure 5: Average daily consumption of residential consumer from the smart grid pilot project in south zone as referred in figure 1**

## 2.3. Methodology

The objective of this analysis is to study the impact of increased renewable penetration on bill savings of residential consumers. The analysis is divided in three parts. In the first part, wholesale electricity prices are modelled using a bottom-up unit commitment model. The wholesale prices are modelled for seven different scenarios. The scenarios and wholesale electricity model output are discussed in detail in section 2.3.1 and 2.3.2 respectively..

In the second part of the analysis, we model the retail rates using wholesale electricity rates as inputs, establishing a standard methodology is to design retail rates. This is discussed in detail in section 2.3.3. In the third part of the analysis, we examine the hourly load profile of residential consumers and calculate electricity bills for all the scenarios using all the modeled tariff mechanisms. We then compare the calculated bills with the base case scenario to study the savings achieved. The methodology is summarized in Figure 6.

### 2.3.1. Scenarios

Seven different scenarios were designed in order to understand the impact of increased solar penetration in the grid. The present generation mix was considered as base case and the remaining scenarios were A-5% (827 MW), B-10% (1655 MW), C-Goal (2000 MW) [46], D-

20% (3311 MW), E-30% (4967 MW) and F- Revised goal (6671 MW) [47]. Scenario C represents the original state target PV capacity and scenario F represents the revised state target, to be achieved by 2022. All inputs were kept constant for each scenario, other than the energy mix as defined in each scenario.

### 2.3.2. Wholesale electricity rates

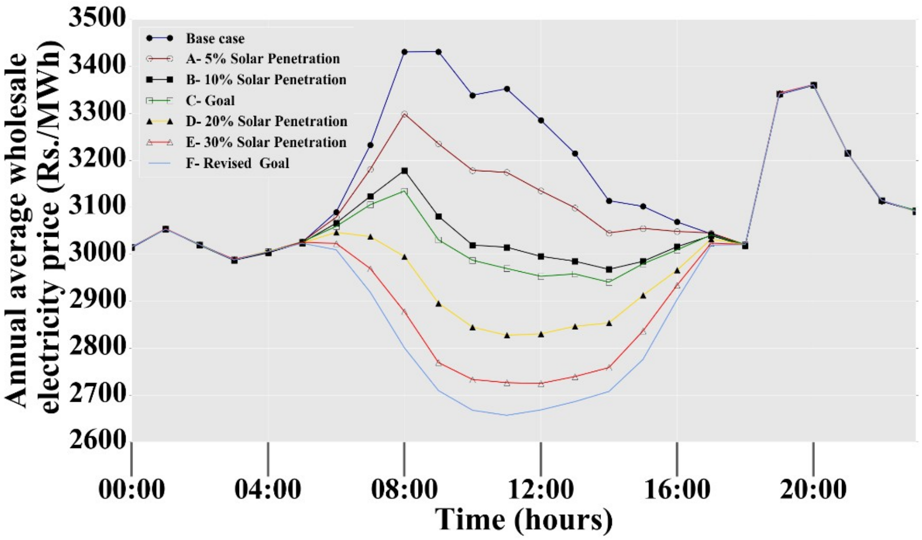


**Figure 6: Average simulated daily wholesale price for various scenarios**

The results of simulated average annual wholesale electricity rates are shown in Figure 7. The wholesale electricity price is determined by marginal cost pricing. Power plants bid into the market at a price equal to their variable costs. These hourly bids are then ordered to develop an hourly supply curve. The hourly market clearing price is determined by the most expensive price of power necessary to fulfill the total demand in that hour. This phenomenon is known as a merit order effect, where the power is dispatched from the sources based on the prices. Merit order refers to the sequence in which the power will be dispatched from different power plants based on the cheapest offer with smallest running costs from the power plants. As the renewables have low operating costs, they push other expensive sources down the merit order. If the power plant has low marginal costs, it will always be dispatched and if the power plant has high marginal costs, it will dispatch only during the hours when its marginal costs are lower than the market price of electricity.

Wholesale electricity price models are to be kept as simple as possible for the sake of transparency and replicability. Thus, the challenge is to identify the main features determining the bidding price of the power plants. The focus of the applied model is therefore a highly detailed representation of the unit commitment of the power plants. The objective function is to minimize the total variable cost while fulfilling the demand requirement. Additional technology specific constraints ensure a more realistic commitment including ramping inertia, minimal up and down times, and must run characteristics. The majority of these constraints depend on technology type and commission year, emphasizing the requirement of a rich data to ensure accurate modeling.

As described above, the focus of the model is a temporal and technological detailed representation of the unit commitment of the power plant park. The costs considered include the variable, fuel, and emission cost of electricity generation. Furthermore, the model includes ramping, no-load, and start-up, and shut-down costs. The most important constraints encompass the demand fulfillment, min and max commitment of every power plant, and part-load generation. Renewable generation is determined through historic capacity factors. [18]

Figure 8 shows average hourly wholesale prices over the range of PV penetration rates considered. As shown in the figure, continued growth of solar in the Karnataka energy mix would lead to a reduction in wholesale electricity rates for most of the daytime peak hours. The initial cost for solar is high but its marginal operating costs are near zero and all of its electricity generation is sold into the power market. This drives the wholesale prices down, replacing more expensive forms of power generation based on merit order effect. Solar reduces the number of peaks in the price curve from two to one. The average price of power in the base case was found to be Rs. 3164/MWh whereas it was Rs. 2974/MWh in scenario E.

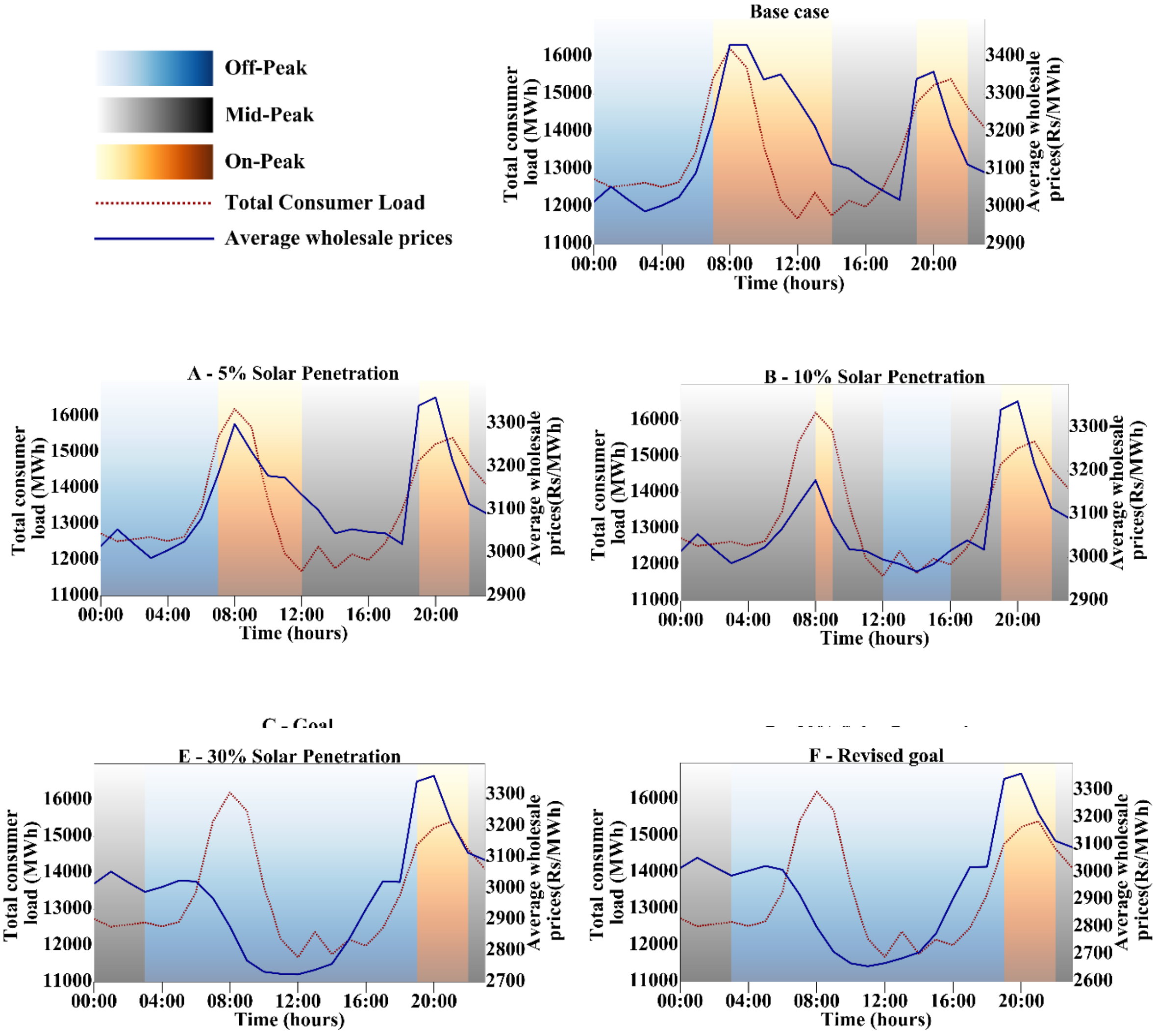
### 2.3.3. Retail Rate Modeling

In order to analyze the impact of increased solar penetration on the electricity bills of residential consumers, four different retail rates were designed using the modeled wholesale electricity prices: a flat time-invariant rate, real time pricing, time of use (TOU) rate, and critical peak pricing. Each of the retail rates were designed such that the total revenue requirement is recovered fully through rates, accounting for reduced sales from self-consumed distributed solar generation.

For designing retail rates some parameters were considered as summarized in table 1. The average tariff was calculated by taking the weighted average of revenue collected from domestic consumers and the number of consumers for each utility. The average daily consumption of an urban residential consumer in Karnataka is 3 kWh. Hence, to achieve that level of daily consumption, the hourly consumption data was multiplied by a scaling factor of 0.31.

**Table *1*: Parameters used for designing retail rate**

| **Parameters** | **Value** |
|---|---|
| **Number of consumers** | 7482102 [48] |
| **Revenue** | Rs. 37.27 billion [48] |
| **Average rate** | Rs. 4.8/ kWh [49] |
| **Scaling factor** | 0.31 |



A fixed monthly charge of Rs.25 per month was assumed for all the retail rates in all the scenarios. A scientific method was developed to map wholesale prices to retail rates, and used for all scenarios considered to maintain the consistency of analysis. While designing rates, the total consumption was multiplied by retail rate and number of consumers as shown in the equation below, to ensure that a full revenue recovery.

$$\textit{Total Revenue} = \textit{Total consumed units} * \textit{Number of consumers} * \textit{Retail rate} \qquad (1)$$

When calculating customer bills , we assumed a demand elasticity of zero.

### Flat rate

The flat rate refers to a pricing mechanism which charges a fixed price for electricity consumption independent of the time or total level of consumption.

The following formula was used to calculate flat rate for all the scenarios.

$$\textit{Flat rate} = (\sum C_h * W_h) / T_c + FC \qquad (2)$$

where $C_h$ is hourly consumer load in MWh, $W_h$ is hourly wholesale electricity price in Rs./MWh, $T_c$ is total consumption in MWh and FC is Consumer Fixed Charge The fixed charge for a consumer was set to Rs. 25 per month, based on existing retail rates in Karnataka.

The flat rates were calculated for each of the seven scenarios considered, summarized in Table 2.

**Table 2: Flat rate under different scenarios**

| **Scenarios/Rates (Rs/KWh)** | **FC=25 per month** |
|---|---|
| **Base** | 4.51 |
| **5%** | 4.46 |
| **10%** | 4.42 |
| **Goal 2000 MW** | 4.4 |
| **20%** | 4.35 |
| **30%** | 4.31 |
| **Revised Goal 6671 MW** | 4.26 |

## Real Time Pricing (RTP)

The real time pricing rate refers to a tariff mechanism that is based on the hourly wholesale rate.

RTP rate is calculated using the following formula

$$Vol_{r_h} = \left(W_h + RTP_{Adder}\right) + FC \qquad (3)$$

Where $Vol_{r\_h}$ refers to the customer's volumetric rate, $W_h$ is hourly wholesale price and $RTP_{Adder}$ is an adder added to ensure meeting the revenue requirements, and FC is the fixed monthly charge. The wholesale price ensures that the utility recovers the variable costs of generation. The adder and fixed monthly charge are necessary for the utility to recover the remainder of its generation, transmission, distribution, and other operational costs.

The RTP adder is calculated using the below formula

$$RTP_{Adder} = \frac{\left(FC_{utility} - FC\right) * Number\ of\ consumers}{T_c} \qquad (4)$$

Where $FC_{utility}$ is utilities' fixed cost, FC is consumer's fixed cost and $T_c$ is total consumed units. Based on the above formula, RTP was calculated for each scenarios. To calculate the customer's annual bill, the hourly rate (calculated using formula 2) was multiplied by the customer's hourly consumption.

## Time of Use (TOU) rate

Under a time-of-use rate, the customer's volumetric rate is dependent on the time at which the electricity is consumed, and is generally higher during peak system load hours. TOU rates can have an off-peak, a mid-peak, and an on-peak period, and can be differentiated by season.

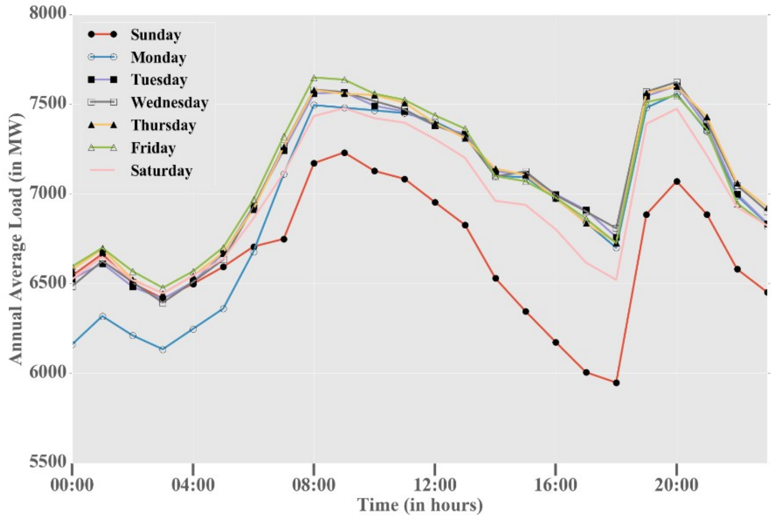


**Figure 8: Annual average load for weekdays**

Figure 9 shows the annual average load profile of the state on a day of the week. The load shape is fairly consistent for all days of the week, with the exception of Sunday, which has a lower average load for most hours. There is no variation in the hour of peak load by day of the week, although the level of peak load is noticeably lower on Sunday.

The three TOU periods (off-peak, mid-peak, and on-peak) were calculated as follows:

1. Annual hourly average wholesale electricity price was calculated based on simulated wholesale electricity prices
2. Based on wholesale electricity prices, two threshold values based on the average rate (one more than average: value ‘a’, and another less than average: value ‘b’) were calculated to define the periods. This value was used to create the three TOU periods. Hours where the rate was greater than the value ‘a’ were determined to be part of the on-peak period. Hours where the rate was less than the value ‘b’ were designated to be part of the off-peak period. All remaining hours in the day were designated as the mid-peak period.off-peakmid-peak
3. No period would be less than three contiguous hours in length other than the on-peak period. When the calculations in step 2 determined a period of one or two contiguous hours, those hours were absorbed in the nearest TOU period.

Using the above steps, three time periods were designed for each scenarios, as shown in figure 8. Once the TOU periods were defined, rates for each of these period were calculated. The off-peak period rate was calculated by taking the average of the wholesale electricity prices for the hours considered off peak period. The mid-peak was set as 75% of the on-peak period rate. The on-peak rate was calculated such that each TOU rate modeled ensures full cost recovery, as per formula 1, including the monthly fixed charge.

The period definitions in each of the scenarios considered change as PV penetration increases, as observed in figure 8. As PV levels start to increase from the base scenario, initially the duration of the mid-peak period increases during the mid-day. But with further increase in PV penetration, wholesale prices are further decreased during the mid-day hours, turning the mid-day hours to the off-peak period. As seen in figure 8, there is a clear shift in the mid-peak and off-peak periods with increased solar penetration and the on-peak period completely disappears in the morning once a certain level of solar penetration is achieved.

## Critical Peak Pricing (CPP)

CPP rate is a variant of the TOU rate in which a critical peak price, which is higher than regular peak price, is charged for few high-priced days in a year as designed by utility.

While designing CPP rates, utilities decide the number of critical events for a year, number of hours than can be declared critical peak timing, and the rate levels for critical peak hours. In one of San Diego Gas and Electric's (SDG&E) CPP rate [50], for example, there are maximum of 18 events annually with a maximum of 7 peak hours per day. In another SDG&E CPP rate [51], CPP events are limited to a maximumof 6 peak hours per day, 4 days per week, 40 hours per month, and 80 hours per year. In another California utility, Southern California Edison [52], there can be maximum 12 events in a year with maximum of 6 CPP hours in a day. In Vermont Green Mountain Power [53], there is a maximum of 8 hours per event with a maximum 150 hours/ year. In New Hampshire Electric Cooperative (NHEC) [54], there is a limit of 12 critical events with 60 hours per year. Similarly, for Virginia Dominion Power [55], there is a maximum of 5 hours per event, 2 events per day, 25 events per year and 125 hours per year.

In the current analysis, we considered a CPP rate with 15 critical events per year with maximum of 8 CPP hours per day. The 15 critical days were selected based on maximum spot prices. During these days, the 8 highest priced hours were considered to be critical peak hours. Other than this, all the design rules for the time of use rate were used to design the CPP, with the exception that critical peak time periods could also be shorter than 3 hours. Hence on critical peak days, there were four time periods, the three TOU periods and the CPP period. The critical peak price for critical hours was set to be twice the normal peak price and critical peak events could not occur on Sundays. The rate for the critical peak hours and non-CPP days were calculated in conjunction, such that the rate levels for the off-peak, mid-peak and on-peak remain constant throughout the year.

In the third stage, electricity bills of the 97 residential consumers were calculated using the designed retail rates.

## 3. Results

The bill savings for each scenario were calculated as percentage savings relative to the base case. For example, for the flat rate, we calculated the percentage savings in scenarios A-F using the basis as bills calculated in base case.

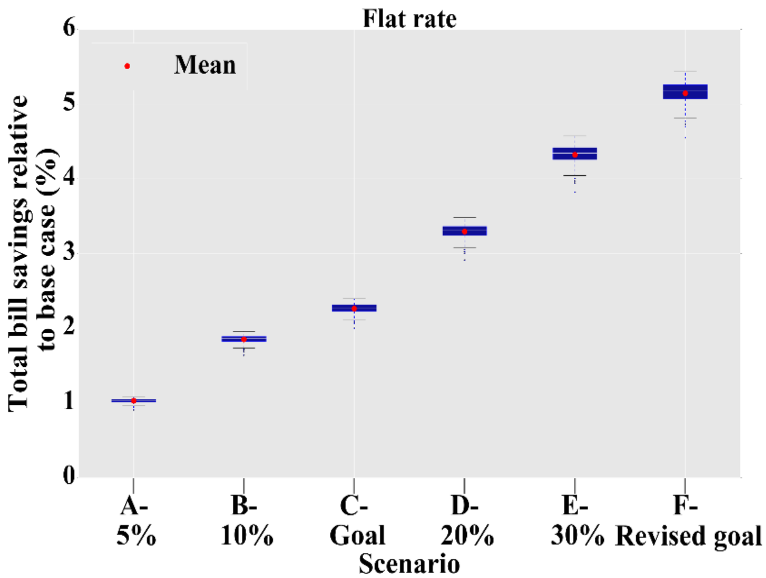


**Figure 9: Bill savings in Flat Rate**

The savings achieved by consumers with the flat rate are shown in figure 10. The residential electricity bill savings increase with increased solar penetration, as does the range of savings. The range of savings for the consumers increased from 1-1.5% in base case to 4.5%-5.4% in scenario F. The increasing savings can be attributed to the reduction in wholesale prices with increasing PV penetrations, as well as the improved coincidence of the peak of consumption of consumers with decreasing wholesale prices with increased solar penetration.

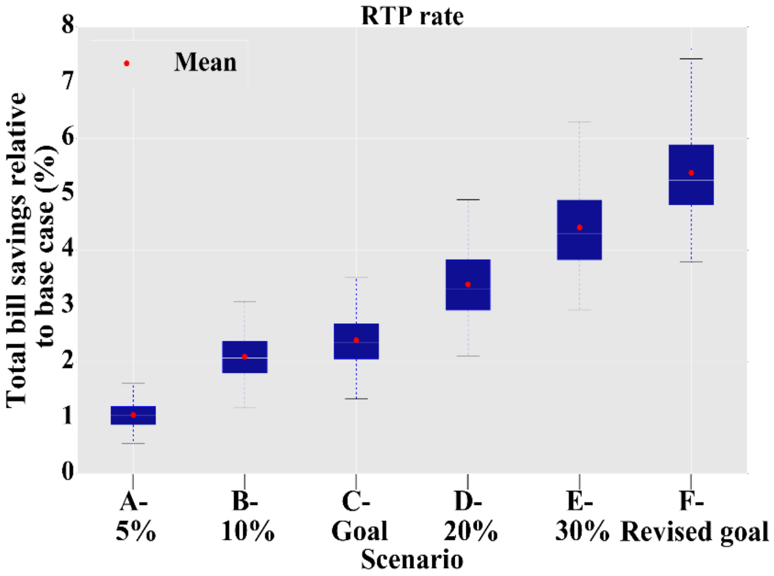


**Figure 10: Savings in RTP rate**

Customer bill savings with the RTP rate are slightly higher than the flat rate, as is the range in saving levels, as observed in figure 11. With the RTP rate, the hourly rate change with the hourly fluctuations in wholesale prices, which is in turn determined by the load profile. While calculating bills, the real time rates were multiplied directly to the hourly consumption. As the solar penetration increases, the rates decrease for duration, where demand is supported by solar energy. With the increase in solar penetration, the morning peaks disappear, and hence the corresponding rate is also reduced. Therefore, based on the coincidence with peak and prices, residential electricity bills are considerably reduced, benefiting both from the time-varying rates as well as the increased solar penetration. The range of savings increases considerably with the increased solar penetration, without any increase in bills.

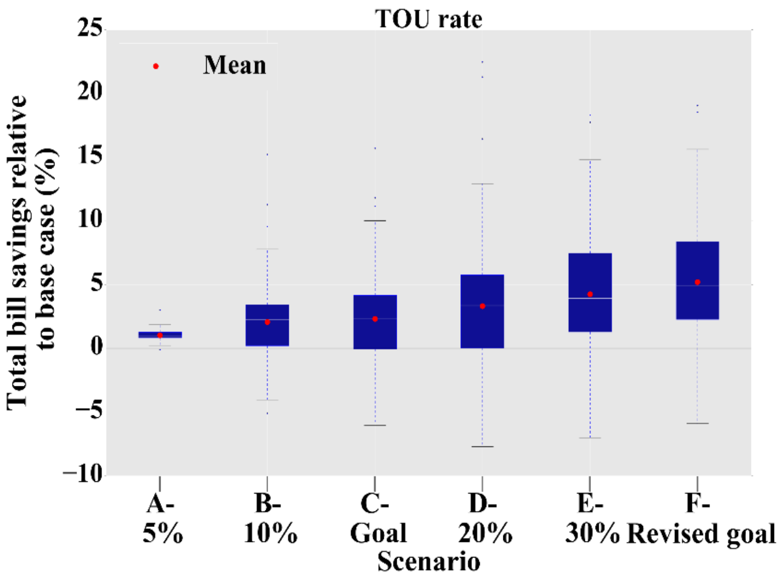


Figure 11: Savings in TOU rate

Figure 12 shows bill savings for consumers under the TOU rate. As observed in the figure, the savings increase for most customers as PV penetration levels increases. Customers with a relatively high load during the mid-day hours have significant electricity bill savings with higher levels of PV penetration, with savings of over 20% in scenario D. Customers with higher electricity consumption during the early evening hours can have increase in electricity bills, as wholesale prices in those hours increase due to increased solar penetration.

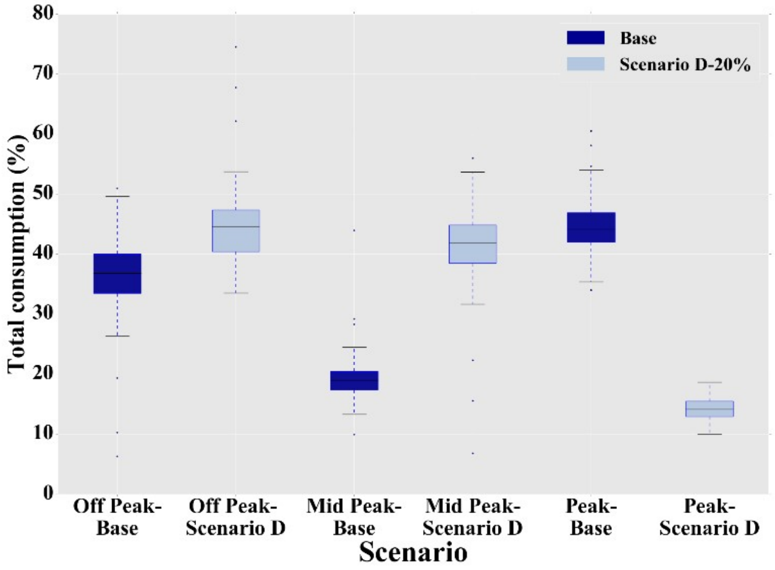


Figure 12: Changes in consumption under different scenarios during different time periods

Figure 13 shows the percentage of consumption in off-peak, mid-peak and on-peak period for base case and scenario D (i.e. a 20% PV penetration). As seen in the figure, electricity consumption during the peak hours in scenario D is significantly lower than for base case. This leads to decrease in electricity bills and hence substantial savings for residential consumers in scenario D when compared with the base case.

For the CPP rate, bill savings are similar to that for theTOU rate, except that there are fewer consumers who have an increase in their electricity bill (figure 14). This can be attributed to the CPP design methodology. As the rates for off-peak, mid-peak and on-peak remain same throughout the year, the increased critical peak rate during critical peak period leads to a rate reduction in the other period, to ensure that the total revenue requirement remains the same. Hence, except for the critical peak hours, the average rate remains less than TOU rate, hence increased savings. The critical peak days were designed based on wholesale electricity prices, so some of the consumers in our sample may have lower electricity consumption during the critical peak periods. This would lead to increased bill savings for more consumers for the CPP rate than for the TOU rate. Also, the range of savings is increased in CPP mechanism as compared to TOU rate.

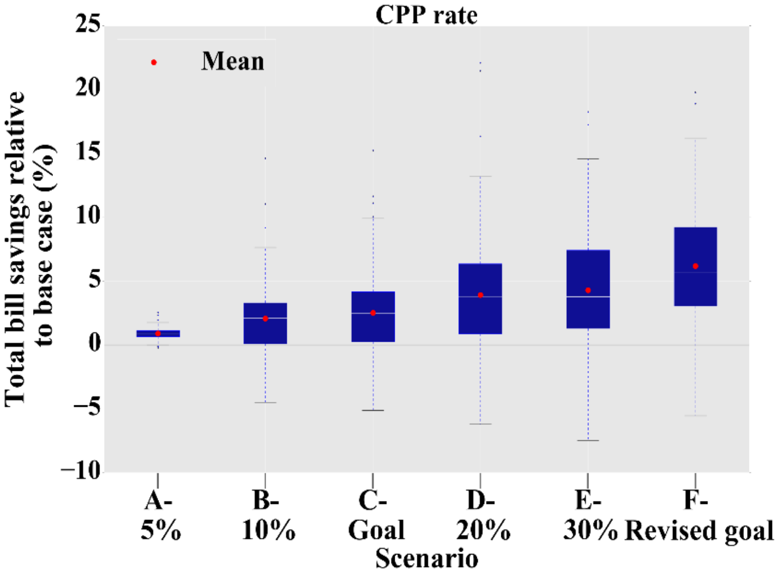


**Figure 13: Savings in CPP**

From the above analysis of bill savings, it is found that, flat rate and RTP provides savings for all the consumers included in this study. In case of RTP, none of the consumers observe increase in their bills, which implies that the wholesale prices and hourly consumption of a consumer are consistent with each other. In some cases, due to variations in time periods in TOU and CPP, a small minority of consumers have increased bills and erosion of bill savings.

## 4. Conclusion

We found that increased solar penetration levels in the state of Karnataka, in India, would have significant impacts on wholesale price profiles, which in turn have impacts on retail rates and residential consumer electricity bills. Given the confluence of increasing prices of coal in India, the push for environmentally friendly alternatives, decreasing solar prices, and ambitious government solar targets, high levels of solar in the electricity mix in the coming years in India is highly probable. Though others are studying the impacts of high solar levels on utilities, generators, and electricity markets, this study has focused on what this means for residential end-users, for a variety of solar penetration levels and retail rates. Our results indicate that higher levels of solar benefit most residential electricity consumers under most rates and scenarios, but time variant rates would prove to be most beneficial. The effect of retail rates on consumer bills is of critical importance for policy makers while designing incentive mechanisms to promote renewables. Renewables have a prominent role in reducing carbon emissions, but require incentives for their growth. Hence, designing retail rates judiciously is of high importance for meeting INDC goals. Our study has found that dynamic mechanisms produce unintended impacts on consumer savings, wherein most of the consumers are better off.

The development of AMI would open up avenues for alternative retail rate mechanisms for consumers which would increase the reliability of power systems in a sustainable manner. This analysis indicates that the dynamics of retail rates will change with increased AMI deployment and PV penetration. The research carried out also has implications for electric utilities and electricity regulators as they ponder changes in electricity rate structures in India.

## Acknowledgements

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