Analysis of residential rooftop photovoltaic systems diffusion in India through a Bass model approach

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ABSTRACT

In this paper, the analysis of the diffusion of photovoltaic systems is performed using the Bass model. The historical data of installed rooftop photovoltaic is not enough for the model, as the installation of photovoltaics was almost non-existent, hence data of solar water heaters is utilized to calculate the parameters for the model. The trajectory of growth for solar water heaters in the market presents a congruence for the growth of solar photovoltaic due to inherent similarities in the technologies and its application. India was used as a case study of the application of this borrowing approach in a market where PV is also used to provide electricity to local communities. Data from solar water heater market in India were used and they indicate innovator parameters of 0.00105 and imitator parameters of 0.12219. The study is significant as it forecasts the diffusion of photovoltaic in the market, which is essential for achieving India’s Intended Nationally Determined Contributions goals and Renewable Energy targets. The results indicate that residential rooftop photovoltaic diffusion will tend to present a slower pace in India than in other markets if no additional policies are implemented to foster this market.

KEYWORDS

PV, market diffusion, Bass model, India, residential market, solar water heaters.

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INTRODUCTION

Decentralization of the energy systems is observed in different countries [1]. Although it can be observed a substantial diffusion of distributed photovoltaic (PV) among households in the last years, different levels of diffusion are being observed depending on the country [2]. Particularly, when one compares developed and developing nations worldwide. Developing nations present a still incipient diffusion in the household sector, as can be observed in India, Brazil and Mexico.

In India, the installed capacity of power plants comprises of 63.6% capacity from fossil fuels, 2% from nuclear, 13% from hydro and 21.4% from renewable energy sources (RES) [3]. Carbon lockin creates a hindrance towards penetration of solar in the system due to dominance of fossil fuels. Solar contributes 7% to the installed capacity. The Jawaharlal Nehru National Solar Mission aims to achieve 100 GW of solar by 2022 [4]. The installed solar capacity is 26 GW by January 2019, and the solar rooftop PV installation is 3.399 GW as of September 2018 [5]. With a compound annual growth rate (CAGR) of 88% [5] in the last 5 years, the growth rate is still lower than the required trajectory for achieving the government's target of 40 GW by 2022 for the rooftop installations. The CAPEX based business models of PV diffusion in India are still the major contributor towards the development of rooftop PV in India, as other models are still not so successful in promoting the growth of the technology. However, OPEX based installation of rooftop PV has increased to 35% of capacity addition in 2018 [5], which shows that such market is extremely dynamic and changing rapidly. The initiatives of the government of India are usually towards the reduction in upfront costs of PV through subsidies, lower interest on debt, tax incentives and tariff benefits.

Figure 1 shows the contribution of the main sectors of the economy towards installed capacity of rooftop PV in India [5].

![Figure 1. Rooftop PV installation based on customer segment in India.](image)

The contribution from the commercial and industrial consumers is high as they pay higher tariffs for electricity and increased subsidies for rooftop PV adds to their savings on electricity. The residential sector comprises of 15% of all the sectors and the encouraging policies from the government like net metering policy and newer business models, which aid in upfront costs, would play a pivotal role in the future growth of residential rooftop PV. A direct impact of a higher percentage in this market would be to help the country in achieving renewable energy goals of emission reductions.

India has 250-300 solar days with a solar radiation of 4-7 kWh/square meter/day [4]. With this abundant solar resource, the diffusion of PV in India would lead to increase in energy...
access through green energy production, energy security and would help to connect rural areas. Although a substantial increase in the electricity access has been observed in the last decade in rural areas, there are still many households without this access [6]. And when PV is used for electrification, battery issues might be an important point that might be considered [7].

The diffusion of new technologies usually follows an ‘S’ curve, which has been used to study the expansion of different processes like adoption of air conditioners, consumer goods, etc. [8]. The main idea of models to capture this diffusion characteristics is to capture the slow increase in the market at the beginning, a faster intermediate phase, and a deacceleration at the end, when the final potential market has been almost reached by the product or the technology. These models are the Cumulative Lognormal, Cumulative Normal, Gompertz, Logistic, Modified Exponential, Weibull and the Bass model [9]. The study of the diffusion of renewable technologies is important for developing strategies to meet the climate goals as well as sustainable development goals. Diffusion modelling is an essential tool for assessment of policies and aids policy makers in revising market mechanisms to achieve the requisite pace for the growth of renewable energy technologies.

There are number of studies that analyse the diffusion modelling for PV growth in different countries. One of the most well-known models in the literature for tackling diffusion of PV systems is the Bass model. The theoretical foundation of the Bass model is one of the major elements for preferring it to other possible S-shaped models since it identifies consumer adoption as the main driver of diffusion [10]. Model parameters are interpreted as representing the role of innovators and imitators in the diffusion of the technology. This model was used to analyze the PV adoption level in several countries [10]. In California, it was found that the coefficient of imitation and the level of education are inversely related and the price-based fluctuations impacts the adoption rates [11]. In an analysis of diffusion of PV in Germany, a system dynamics model was used to study the impact of feed in tariffs on PV adoption. It was observed that the policy makers should make decisions on feed in tariffs as soon as possible to maintain trust in the consumers for continued promotion of the technology. There has been a significant growth in the demand of PV in Germany in the last decade that has led to a decrease in prices. The market for small scale PV is almost saturated and a mix of Renewable Energy Target (RET) would help in achieving the RE goals. In addition, public policy plays a significant role in transition towards a greener economy [12].

Another study analyzed the household level innovation diffusion model for Ontario, Canada using discrete choice experiments to predict the probabilities of the time of adoption of PV. The study shows that awareness among consumers about technology and savings achieved have a critical impact on the adoption rate and emphasized importance of effective education [13]. In a study conducted for households in Italy, an agent-based model was used to study the diffusion of PV. The results indicated that the feed in tariff scheme has boosted the PV adoption, but it would continue at a slower pace. The stepwise reduction in financial incentive would lead to stable PV diffusion as compared to steep reduction in incentives, which would drop the diffusion process significantly [14]. Studies were also conducted in the Netherlands regarding adoption factors [15] and discussions about feed-in-tariffs for solar were carried in Japan [16] and Germany [17].

In India, a forecast of electricity generation using a nonlinear Bass diffusion model indicates that the growth of fossil fuel based resources will be dominant; however, renewables will contribute to 22% of the generation mix by 2030 [18]. Since distributed PV diffusion in the residential sector is still in the initial stages in India, applying Bass model to forecast diffusion at PV market can be tricky if parameters are not properly chosen, since there is not sufficient historical data to fit a Bass model curve and estimate the model equations parameters.

Some work has been conducted in developing markets, as Brazil, with a borrowing approach from the solar water heater (SWH) market [19], which is a much more diffused technology and presents more consistent values for the model parameters. However, in this market, PV is more used as a replacement way of existing source of already connected
communities [20]. To the best of the knowledge of the authors, there is no papers in the literature that show how this “borrowing approach” applies to markets where PV is also used to provide the first source of electricity to local communities. In this paper, PV diffusion in a residential market with such characteristics is analyzed using this approach. India is used as a case study, projecting values for future diffusion in this market.

This paper is organized as follows; section 2 presents the methods used for calculating final potential market and Bass model parameters of SWH market; section 3 presents the results of borrowing the parameters from one market to another and a brief discussion of such results; in section 4, a conclusion with the main findings and potential suggestions for the future work is presented.

METHODS

Using the systems dynamic approach, a Bass diffusion model is analyzed for studying the rooftop PV adoption rate in a market with PV also being used as a source of primary electricity to local communities. India is used as a case study.

In the first step, the data is collected for historical installed capacity of rooftop PV and solar water heaters in India. The data is collected from reports of Ministry of New and Renewable Energy (MNRE) [4] and reports from Bridge to India, a consulting company in the renewable energy market in India [5]. Then, the final potential markets of SWH and PV are estimated, based on the total number of households in India. In the sequel, the Bass model parameters are estimated for the SWH market, based on diffusion of SWH in India. The calculated parameters are used as proxies for the incipient rooftop PV market. Finally, a comparison is drawn between the projected diffusion of rooftop PV based on SWH parameters and diffusion of PV based on Bass model parameters from a more consolidated household PV market, as the USA.

As residential rooftop PV diffusion in India is still incipient, a robust dataset is not available from which parameters to model the adoption of distributed PV technology can be derived, up to its final diffusion. Hence, SWH historical data are used to obtain the Bass model parameters, based on a similar approach in the literature [19]. This approach is justified because the SWH market carries several similarities with the rooftop PV market. Both technologies are mostly rooftop-mounted and use the solar resource as input. Moreover, they are being mainly developed under similar business models, since financial returns are obtained from electricity bill savings across subsequent months. Demographic similarities for both markets should also be pointed out, since both markets are composed of individual and distributed owners of houses, who are able to install a system in their rooftops only based on individual decisions.

Final potential market

The final potential market is the total potential capacity that could be installed on rooftops for PV and SWH in India. It is calculated by an external estimation method, based on demographic, technological and economic features of the country [19], as it is not recommended to estimate them by fitting historical data in a S-curve, which could lead to significant underestimations [21], [22]. The data for filtering each layer is collected from the government of India websites for number of households and percentage of rural and urban households [23], [24]. Data from literature [25] and [26] were also been considered as explained in each topic.

The potential market at \( t = 0 \) and at \( t = T \) are estimated considering the following procedure, in the demographic, technological and economic layers, as represented in Figure 2.
The final potential market is estimated based on the demographic, technological and economic considerations.

**Demographic Layer**

- Retrieve the total number of households in India, $H_{\text{total}}$. This number is obtained from the Indian Government Statistics based on [23], [24].

- Estimate of the total number of houses owned by the household, $H_{\text{owners}}$, since rental households cannot decide to install the technology by themselves:

  $$H_{\text{owners}} = H_{\text{total}} \times f_{\text{owners}}$$  \hspace{1cm} (1)

  $f_{\text{owners}}$ is considered the percentage of total households owned by the people residing in the households.

**Technological Layer**

- Estimate the total number of available households $H_{\text{cap}}$, excluding those with shadow, tanks, antennas, and a cross-competition between SWH and PV for the same space. This capability factor is given by $f_{\text{cap}} = 0.85$ for PV, according to [25] and $f_{\text{cap}} = 0.75$ for SWH, due to additional necessary modifications in the plumbing systems for SWH technology:

  $$H_{\text{cap}} = H_{\text{owners}} \times f_{\text{cap}}$$  \hspace{1cm} (2)

- Estimate the total capacity ($C_{\text{cap}}$) of installed power for PV and area for SWH, considering that rooftops will have on average a SWH of $\bar{c} = 2\text{m}^2$ and a solar panel of...
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\[ \bar{c} = 3 \text{ KWp for PV} \] [25] where \( \bar{c} \) is the average size of the SWH in m\(^2\) and in KWp for rooftop PV:

\[ C_{cap} = H_{cap} \times \bar{c} \] (3)

**Economic layer:**

- Estimate the maximum market share \( mms_0 \) at \( t = 0 \):
  \[ mms_0 = e^{-f \times PB_0} \] (4)

  where \( f \) is a sensibility factor, estimated in 0.3 by [26] for PV market, and \( PB_0 \) is the payback time in years. Final payback time of 3 years for PV and 1 year for SWH for the final diffusion period of the analysis have been considered.

- Calculate the initial potential market \( m_0 \) by multiplication of the estimations of capacity with the fraction \( mms_0 \) obtained in the previous step:
  \[ m_0 = C_{cap} \times mms_0 \] (5)

- Calculate \( m_T \), as estimated by (6), taking the value of \( t = T \) as a long-term period for diffusion. In this approach, a yearly household increase at a rate (\( \text{rate}_\text{pop}_T \)) of 2% for each year in this period was considered:
  \[ m_T = m_0 \times \text{rate}_\text{pop}_T \] (6)

**Innovation and imitation parameters in the Bass model**

For estimating such parameters, the Bass model approach was used, which is a well-established model in marketing and economics proposed by Bass [8]. It considers that a diffusion process occurs in an S-shaped curve, which is obtained on the Bass model by (7) and (8). \( F_t \) represents the cumulative fraction of adopters and \( Y_t \) represents the cumulative adoptions at time \( t \):

\[ F_t = \frac{1 - e^{-(p+q)(t)}}{1 + \frac{q}{p} e^{-(p+q)(t)}} \] (7)

\[ Y_t = mF_t = m \frac{1 - e^{-(p+q)(t)}}{1 + \frac{q}{p} e^{-(p+q)(t)}} \] (8)

The parameter \( p \) is used to model the innovation and represents the role of innovators in the diffusion process. The parameter \( q \) is the coefficient of imitation and it models the “word-to-mouth” diffusion process. The parameter \( m \) is the final potential market, which was previously discussed. In this paper, the values of \( p \) and \( q \) were estimated by nonlinear curve fitting with historical data of SWH and \( m \) by the demographic, technological and economic estimations for
RESULTS AND DISCUSSION

This approach is applied in the Indian market. This section presents a case study and a discussion of the diffusion results in this particular market.

Case study

India was chosen to represent an application of this approach based on the hypothesis of the paper. SWH diffusion parameters for India were obtained by a nonlinear curve fitting with historical data and presented in Table 1. Statistic values are also presented.

Table 1. Parameters for SWH market in India based on the annual historical data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>p</th>
<th>q</th>
<th>( m_T^* ) (million m²)</th>
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<tr>
<td></td>
<td>0.00105</td>
<td>0.12219</td>
<td>205.46</td>
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\*\( m_T^* \) corresponds to the value of estimated final potential market in million m²

\*\*h from a ttest; since it equals zero, it does not reject the null hypothesis at the 5% significance level that residuals have zero mean and unknown variance.

Figure 3 depicts how SWH market is diffusing in India, considering the parameters obtained with historical data up to 2016, and the final potential market estimated by this methodology.

It can be seen that SWH market will converge to the final potential market after year 2050. In year 2016, the diffusion was still nearly 5% of the total final potential market estimated of 205.46 million m². Estimations from literature indicate that 100 million m² will only be achieved near year 2030 [18]. This approach projects such milestone for around year 2035, based on the historical data and the final potential market estimation.
In Figure 4, the parameters from the SWH market are used to project the diffusion of rooftop PV systems in the residential market in India, up to a final potential market estimated of nearly 140 GW in the whole country by this potential market methodology. In the x-axis, there is the years and in the y-axis the total installed distributed household solar power (MW) The comparison of the diffusion when considering parameters obtained from a study in USA [27] and diffusion when the parameters are obtained from a SWH market is done. The green curve represents the diffusion when SWH parameters are used and the black curve when parameters from the USA market are used. The first initial results of residential rooftop PV diffusion in India are shown highlighted in Figure 5.
It is observed that the rooftop PV diffusion in India is progressing at a slower pace in the years to come than what is estimated in literature for other PV markets, like USA [27], which presents a stronger initial diffusion. Moreover, the historical data (red dots) aligns better to the diffusion path (green curve) obtained with the local SWH data, as highlighted in the Figure 5. This study corroborates more conservative projections observed in the literature for Indian grid-connected solar PV market [18], in which cumulative installations will achieve 35 GW in year 2030 [18]. Considering that currently percentage of residential installations (15%) is lower than in other parts of the world and tends to increase in the years to come, this number could range from 5 to 20 GW, which is inside estimations with SWH $p$ and $q$. Using Bass model parameter from USA, it would be nearly 100 GW, far from what is projected in this paper.

Considering that similarities of SWH and rooftop PV markets are sufficiently strong to be used as a proxy, one can observe that additional policies to foster PV technology could be necessary in
order to accelerate rooftop PV diffusion in India, and therefore accomplish renewable energy goals. Also, the present research indicates that it would be possible to achieve 5-20 GW of residential installation by 2030 whereas the National Solar Mission of India, the target is to achieve 40 GW of rooftop PV (includes industrial, public and commercial installations along with the residential) by 2022. This seems difficult to achieve as the installed rooftop PV capacity in 2018 was 5.2 GW.

CONCLUSION

An initial estimation of how rooftop PV will tend to diffuse in the years in a market where PV is also used as a primary source of electricity to local communities was presented. India was used as a case study. From the total number of households, the final potential residential rooftop PV market were estimated. On the other hand, from the SWH historical data, technology diffusion parameters were estimated according to a Bass model approach. After borrowing the parameters from one market to another due to market similarities, these results show that PV diffusion in India will tend to be much slower than what is observed in other residential PV markets, like USA, if no additional incentives are considered in this market. Moreover, when the use of PV technology as a primary source of electricity might turn this diffusion even slower, since it demands a parallel diffusion of additional technologies, such as batteries. Future work could explore different pathways: a comparison of different diffusion methodologies and a refinement of the potential market estimation methodology could be used to improve estimation for India using this approach. Additionally, an estimation for USA market using this approach could be another important path of validation of the methodology in a general approach.

ACKNOWLEDGMENT

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NOMENCLATURE

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<th>Abbreviations</th>
<th>Description</th>
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<td>PV</td>
<td>Photovoltaics</td>
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<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>SWH</td>
<td>Solar Water Heater</td>
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<tr>
<td>mms</td>
<td>Maximum Market Share</td>
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REFERENCES