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Research article

Evaluation of economic feasibility of rooftop solar energy systems under multiple variables

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Abstract: Rooftop harvesting of solar energy is a promising method to provide a great portion of household energy requirements in many parts of the world. However, the cost of solar energy systems sometimes makes the exploration of rooftop solar energy systems not attractive to property owners. This study evaluates the economic factors that could affect the decision on whether to consider the installation of solar energy systems using the estimated time that the cumulative solar savings would become positive. The economic implication of increasing the micro-generation capacity of individual households, and the impact of varied interest rates, and subsidies were also evaluated. Among the three factors that were presented, the result showed that increasing the amount of electricity that is allowed to be generated from individual rooftops will result in the highest economic attractiveness for end-users. This is also expected to move the world closer to the goal of sustainable management of non-renewable resources for present and future generations. Increasing the micro-generation capacity of electricity from photovoltaic (PV) rooftops by individual households without increasing the electricity distribution fees results in a reduction of the time to reach positive solar savings. In addition, increasing the micro-generation capacity of electricity from PV rooftops is expected to contribute to a reduction in the greenhouse gas (GHG) emissions from the electricity grid for the entire community. This study recommends the encouragement of policies that allow for the maximization of electricity generation potential from rooftops of residential and industrial buildings.

Keywords: solar energy; resource depletion; energy policy; economic sustainability; market penetration; solar economics

1. Introduction

A reliable energy supply is crucial for the sustainable socio-economic development of every nation. Access to electricity has a significant effect on telecommunication services, healthcare and water supply. Meanwhile, in some parts of the world, many people do not have access to electricity from the main grid [1]. A considerable portion of energy use worldwide is from fossil fuels. Various works have mentioned the concern of the eventual depletion of fossil fuels. Some researchers [2] noted that in addition to the release of carbon emissions, the regular usage of fossil fuels leads to depletion. Hence, the exploration of renewable energy ought to be given a higher priority to ensure that this technology is well developed to provide sustainable electricity at an affordable rate while helping to reduce the concerns about resource depletion. Solar energy is abundant, non-polluting, and free [3]. Due to its widespread availability, solar energy (especially through solar photovoltaics technology) is widely used around the world [4]. Rooftop solar photovoltaics can contribute to energy independence while helping to reduce the concern around greenhouse gas (GHG) emissions. Lower GHG emissions from widespread solar photovoltaic (PV) implementation can help in addressing the climate change issue [5]. With the aid of solar cells, solar PV power generation converts solar radiation directly into electricity [6]. PV is recognized as a cost-competitive and sustainable technology that provides a clean energy source while contributing to reducing global environmental problems [7]. In the last 20 years, both in Europe and around the world, PV installations have become a popular form of renewable energy sources [8]. Another study [9] also mentioned that rooftop solar PV systems can contribute significantly to energy transition in Europe. Grid-connected solar power plants help to achieve a reduction in the polluting emissions from fossil power plants [10].

Households that adopt solar PV panels can reduce their average electricity unit cost by either self-consuming the self-generated electricity or by feeding the generated electricity into the grid [11]. However, it is important to note that among other things, the profitability of solar PV systems is dependent on the total cost of the solar energy systems, the available space for the energy systems, and the government regulations in the locality. Multi-dimensional indicators that affect the estimation of solar energy potential include the economics of solar products, government policies, technological development, local solar energy resources, land cover, etc., [3]. Among other factors, social acceptance is one of the factors that need to be considered in the selection of large PV power plants [12]. In addition to factors such as aesthetics, political climate, perspectives and pressures from influential stakeholders (especially those who have high economic and political powers in the community), social acceptance can be affected by the economic feasibility of solar PV systems. In the effort to provide electricity for nearly 1 billion unconnected people in developing countries, there are high hopes for market-based dissemination of off-grid technologies to complement expensive grid extension [13].

PV rooftops have great potential for reducing reliance on conventional energy while helping with energy security during emergencies. PV rooftops also have significant potential in remote areas [5]. As the global population grows, the need for energy for sustainable development increases. Hence, there is a need for continuous improvement in the approach to renewable energy harvesting to supplement and better manage global 'non-renewable' energy reserves for present and future generations. Solar energy generation from rooftops has not come without various challenges. However, these challenges can be addressed by various novel approaches to maximize the potential for solar energy harvesting in residential communities. In some places, usable rooftop areas are limited by shading effects and obstacles on the roof. In a day, the shadow profile on a building rooftop varies constantly due to the ever-changing position of the sun, resulting in a significant variation of the usable rooftop areas at different hours [14]. Complex shading effects and rooftop availabilities make the planning of large-scale distributed rooftop systems a critical challenge [15]. This challenge can be mitigated by improved city planning while ensuring that no building causes an undue shading effect on another building. Roof designs to maximize solar harvesting potential would also be helpful. In high-density cities, there is a huge need for optimal packing and planning of large-scale distributed rooftop PV systems. The major barriers to large-scale deployment of rooftop PV systems are lack of awareness among consumers about the system, lack of manufacturing facilities, high upfront cost, lack of skilled workers, lack of business models and regulatory challenges [16]. Technical experience in the manufacturing sector and limitations in domestic technology are some of the major barriers inhibiting the progress in rooftop adoption [5]. This challenge can be addressed by the intentional creation of more solar panel manufacturing facilities in different communities to support local needs and also to provide adequate export to other regions around the globe.

The energy policy in different places mitigates against adequate exploration of solar energy. In some places, complex shading effects on rooftops of buildings are not a major issue. The amount of electricity that can be generated from the rooftops of the buildings is limited to household use while potential opportunities for sharing of excess energy that is generated through a 'community share program' can be explored. A practice that limits the amount of solar energy that can be generated from rooftops to household use reduces the potential for solar economics to be very attractive. On the other hand, adequate policy upgrades to maximize the use of solar energy as a means for sustainable management of non-renewable natural resources can help increase the economic sustainability outlook while improving the market penetration for renewable energy systems. There is interest in the exploration of solar energy systems for different applications. Solar energy can be exploited to produce heat energy through solar thermal collectors and also generate electricity through solar (PV). A combined photovoltaic-thermal (PVT) system is attracting interest to maximize the benefits of solar energy [17]. Some researchers [18] noted that solar vehicles (renewable energy-based systems) with no emissions of greenhouse gases can be considered a substitute for modern-day automobiles. The use of rooftop solar photovoltaics and batteries to provide energy for electric buses is seen as a good approach to the reduction of GHG emissions and street-level air pollution in high-density cities [19]. Some researchers [20] mentioned the application of solar energy in trains. Another report [21] made mention of solar bike paths in the Netherlands. Although there are several advantages to the use of solar energy, some other factors mitigate against its application at various times in different places around the globe. Disadvantages of solar electricity include its limitations by weather. Since solar panels need sunlight to work well, their performance drop during cloudy and rainy days [22], making storage of electricity that is produced a necessity. The economic attractiveness of solar energy is also an important factor that can influence the effort to increase the penetration of solar energy systems. Efforts to have the most efficient and optimum services with minimum cost are essential in every industry [18]. Some researchers [23] reported that due to a high discount rate and weather with medium annual solar radiation intensity, the economic competitiveness of photovoltaic/thermal technology is not very high in the city that was studied in their research. This shows the need for continuous study on how to increase the economic competitiveness of PV modules for all the applications where its use is desirable.

2. Materials and methods

2.1. Research objective

The objective of this study is to evaluate the impact of multiple variables on the economic feasibility of rooftop solar energy systems.

This research objective is evaluated by: The time for the cumulative savings on investment in solar energy to become positive.

2.1.1. Research questions

(1) Is roof-top solar energy economically feasible?

(2) What measures can be taken to enhance the economic feasibility of solar energy systems?

(3) What areas of improvement exist to improve the economic feasibility of roof-top solar energy?

(4) What impact do interest rates, subsidies and increased micro-generation capacity have on the economic attractiveness of solar energy systems (as measured by cumulative solar savings)?

2.2. Methodology

Records of electricity bills obtained for 5 different households allow for an evaluation of the household electricity usage for the year. It also allows for an estimation of the capacity of solar panels that can serve the electrical energy needs of the household for the year. Quotes for the installation of solar panels that will cater to the electrical energy needs of the households were received from a representative of a solar energy installation company. To evaluate the attractiveness of the cost of investment in solar energy systems, the cost estimate that was received from a solar panel installation company for one of the five residential families and the monthly distribution/transmission fees for electricity from the grid were used to estimate how long it will take the savings on solar investments to become positive. The time taken for the cumulative solar savings to become positive was also evaluated with varied interest rates while keeping micro-electricity generation capacity constant. The solar savings for each year were calculated by subtracting the earnings from micro-electricity generation from the sum of the yearly loan payment, the transmission/distribution fees, administrative fees, and tax. Note that the calculation for solar savings will be dependent on the different kinds of costs that are associated with the production and use of solar energy. Among other things, a previous work [24] considered the cost of incremental insurance and maintenance in the calculation of solar savings.

The principal loan amount (P_l) illustrated in Eq 1 is calculated by subtracting the government incentives (G_i) and the downpayment (D_p) from the sum of the quote from the contractor (Q_t) and the tax (T_x). i.e.,

$$P_l = Q_t + T_x - G_i - D_p \tag{1}$$

This study

(1) Evaluate the impact of varied interest rates on time for solar savings to become positive.

(2) Evaluate how government incentives influence the time for solar savings to become positive (i.e., indirect influence on the attractiveness of solar investments).

(3) Evaluate how the increase in the microgeneration credit affects the time for solar savings to become positive (indirectly increasing the attractiveness of electricity generation from solar power).

(4) Evaluate how the increase in microgeneration capacity of rooftop solar energy can contribute to the reduction of GHG emissions.

The number of years for cumulative solar savings to become positive with varying interest rates (1%, 3%, 5%, and 7.2%) was evaluated without increasing the electricity distribution and administrative fees. The impact of the increase in the transmission fees on the time for the cumulative solar savings to become positive was evaluated at a 1% interest rate. The cumulative solar savings is a sum of the solar savings beginning from the time of installation of the solar panels until the period that is being evaluated.

2.2.1. Project assumptions

It is assumed that the revenue from micro-generation, administrative fees, and distribution fees increase with the rate of inflation. The number of compounding periods is assumed to be 365 for all the years that were evaluated. Although the quotes that were received for the installation of solar panels that will cater to the households vary, the estimated principal loan amount for analysis of the economic feasibility of solar panels for this study is $21,735.00. Note that it is likely that the distribution fees may be reduced after the installation of solar panels (depending on local rules and regulations around distribution fees). However, in evaluating the impact of distribution fees, for this illustration, it is assumed that the electricity distribution fees are unchanged, except when it is scaled up to evaluate the impact of distribution fees on increased microgeneration potential from individual rooftops.

3. Results

3.1. Factors that can affect the acceptance of solar energy systems

3.1.1. System costs

Among other factors, the price of solar panels as relating to the upfront cost, and the expected payback period are important factors that can affect the widespread use of solar energy.

3.1.2. Cost of installation of solar energy systems for residential buildings

The cost of installation of solar panels differs from one project to the other. Various factors such as the cost of the PV panels, the cost of associated materials for installation, labor cost, costs to purchase/rent the installation equipment, and the technicality of the job may affect the cost of the installation of solar panels. A previous work [25] gave the cost of installation of solar panels for various communities in Canada. Table 1 shows the electricity usage (for a 12-month period), and estimates from a solar panel installation company for the cost to install solar panels for five households.

The author [26], reported that the average installation cost per watt ranges from $2.34–$2.59 in Ontario to $2.51–$2.77 in Alberta to $3.53–$4.32 in Newfoundland and Labrador, and to $4.00+ in Nunavut. To compare the cost from the contractor with data from previous work, the average installation cost for solar panels in Alberta is multiplied by the estimated capacity (watts) for the solar panels for the household. This means that for a 9.7 KW system above, the estimated cost for installation of solar panels in Alberta will be in the range of 9700 watts × $2.51/Watts to 9700 × $2.77 /watts = $24,347 to $26,869. The study further noted that the actual price of the system depends on different factors including the quality of the equipment that is used, the size of the system and the complexity of the job. It was also noted that the installation prices can easily go higher than $3 per watt for high-quality installers and premium equipment. The above high investment cost for the installation of solar panels indicates that there is a need for adequate measures to improve the economic attractiveness of solar energy systems. Table 2 shows the parameters that were selected as base conditions for further analysis of how multiple variables can affect the economic attractiveness of solar energy systems.

Table 1. Estimated cost (price quote) of installation of solar panels (2023).

Customer	Annual electricity consumption (kWh)	Capacity of panel recommended by the solar contractor (kW)	Estimated cost (by contractor) to get the customer set up with solar panels
Residential Customer 1	5771	5.2	$16,000.00
Residential Customer 2	8206	8	$23,000.00
Residential Customer 3	10350	9.7	$25,500.00
Residential Customer 4	13194	12	$30,000.00
Residential Customer 5	10664.5	9.5	$25,000.00

Table 2. Parameters for base conditions of the evaluation of economic attractiveness of solar energy systems under multiple criteria.

Parameters	Base conditions
Quote from contractor (Residential customer # 2)	$23,000.00
Tax	$1,150.00
Government incentives for installing solar panels	$-
10% Downpayment	$2,415.00
Principal (loan amount)	$21,735.00
Amortization Period (years)	25
Annual Nominal Interest rate	0.072
Number of compounding periods	365

3.1.3. Economic analysis of solar panels

Multiple variables such as initial cost of investment, interest rates, subsidies, micro-generation capacity, electricity distribution fees and other associated costs can have an impact on the economic attractiveness of solar energy systems. Interest rate is the amount that a lender charges a borrower for the use of its asset. i.e., the amount the bank charges people when money is borrowed from the bank. The discount rate is the interest rate that the Federal Reserve Banks charge commercial banks and depository institutions for overnight loans. While the discount rate can be used to calculate the present value of future cash flows, the interest rate is not used in present value calculations [27]. Another work [28] reported that the prime rate will increase to 7.2% as the policy rate is increased to 5% by the Bank of

Canada. The economic analysis in this study is based on the assumption of a 5% discount rate from the central bank and a 7.2% interest rate from the commercial banks. The solar energy process economics described by an author [29] indicates that given a discount rate d, the present value or present worth, P (Eq. 2) of a future cash flow F, in n years from now is expressed as:

$$P = \frac{F}{(1+d)^n} \tag{2}$$

Given a yearly inflation rate i, and a purchase cost E at the end of the first year, a future cost at the end of n years can be represented as illustrated in Eq 3:

$$F = E(1+i)^{n-1} \tag{3}$$

Canadian inflation rate for 2022 is 6.8% [30]. Assuming an annual inflation rate of 6.8% for the distribution fees, and the administration fees, the expression in Eq 3 is used to forecast the future values of the administrative cost, the distribution fees and the microgeneration credit. Note that the inflation rate fluctuates over time. A similar expression by some authors [24] for the future cost. i.e., for a cost, E (that is incurred at the end of the first period) having an inflation rate i, the recurring cost F, at the end of the nth period can be represented as presented above.

The work [24] noted that the total present worth of n future payment is represented as:

$$E\left[\sum_{j=1}^{n} \frac{(1+i)^{j-1}}{(1+d)^j}\right] \tag{4}$$

Where $PWF(n, i, d)$ is the present worth factor expressed as $\left[\sum_{j=1}^{n} \frac{(1+i)^{j-1}}{(1+d)^j}\right]$

$$when\ i \neq d, \qquad PWF(n,i,d) = \left[\frac{1}{d-i}\left(1-\left(\frac{1+i}{1+d}\right)^n\right)\right]$$

$$when\ i = d, \qquad PWF(n,i,d) = \frac{n}{1+i}$$

Some other authors [31] gave various formulas for economic analysis. For example, the future value of a single payment F_u was represented in Eq 5 as follows:

$$F_u = P_r(1+i)^n \tag{5}$$

Where F_u is the amount that will be paid back in future (at the end of n years) if the condition of the loan is such that an interest, i is included at a compound rate, and P_r is the principal. When payments are made at regular intervals, where A (Eq. 7) is a uniform end of period payments that continue for period n, the uniform series of payment formula for the total equivalent amount F_u at the end of period n is expressed in Eq 6 as:

$$F_u = A\left[\frac{(1+i)^n - 1}{i}\right] \tag{6}$$

$$A = \frac{i * P_r}{1 - (1 + i)^{-n}} \quad (7)$$

An explanation of mortgage interest calculation was provided in a previous work [32]. An explanation of effective interest rates was also provided in another work [33].

$$i_{eff} = \left(1 + \frac{r_{nom}}{N_{comp}}\right)^{N_{comp}} - 1 \quad (8)$$

The effective interest rate (Eq 8) was used to calculate the monthly interest rates. This is related to the monthly interest rate as illustrated in Eq 9.

Where r_{nom} is the nominal interest rate, N_{comp} is the number of compounding periods, i_{eff} is the effective annual interest rate, and m is the number of months in the year. The periodic interest rate (monthly), i_m was calculated using the formula below:

$$i_m = \left(\sqrt[m]{1 + i_{eff}}\right) - 1 \quad (9)$$

For the evaluation of monthly payments in this study, the periodic payment was calculated by substituting the monthly interest payment (Eq 9) as the interest in the uniform end-of-period payment (Eq 7). The amount contributed towards paying off the principal in every month is calculated by subtracting the interest accrued within that month from the monthly payments. The new balance owing is calculated by subtracting the amount that was contributed towards paying off the principal (including any extra payments made) from the balance owing at the end of the previous period. i.e.,

The new balance owing = Balance owing at the end of the previous period − the amount contributed towards the principal during the present period − extra payment made during the present period.

At an interest of 7.2% and no government subsidy for solar panels, Table 3 shows the cost of the loan, the yearly interest, principal payment, remaining principal and the present worth of interest payment.

Total interest on the principal (for z number of periodic payments) is obtained by summation of the interest accrued in each period as shown below. For the illustration used, interest i was assumed to be constant for the amortization period.

Where P_0 is the original principal loan amount, the total interest accrued from year $x = 1$ to year $x = z$ is the sum of the product of the remaining principal on the loan and the interest rate i.

Total interest accrued = $\sum_{x=1}^{z}[(P_0 * i_1) + (p_1 * i_2) + (P_2 * i_3) + \cdots \ldots (P_{z-1} * i_z)]$.

The expression P_{z-1} represents the balance owing at the end of the preceding period. Note that there may be some differences in the results from economic analysis. For example, there may be some differences in the total amount that will be paid in interest and the monthly payment (depending on the assumptions and how it is calculated). This study recommends a review of how interest rates are calculated to ensure consistency and also to ensure that people are not overburdened by the impact of interest rates on loans. From Table 3, it is obvious that the total present worth of interest payment is significant at a 7.2% interest rate.

Table 3. Cost of loan for solar panels on consumers at an interest rate of 7.2%.

S/No.	Yearly payment	Principal payment	Interest payment	Remaining principal	Present worth of interest payment
1	$1,880.34	$321.37	$1,558.97	$22,678.63	$1,484.73
2	$1,880.34	$345.36	$1,534.98	$22,333.27	$1,392.27
3	$1,880.34	$371.14	$1,509.20	$21,962.13	$1,303.70
4	$1,880.34	$398.85	$1,481.50	$21,563.28	$1,218.83
5	$1,880.34	$428.62	$1,451.72	$21,134.66	$1,137.46
6	$1,880.34	$460.61	$1,419.73	$20,674.04	$1,059.42
7	$1,880.34	$495.00	$1,385.34	$20,179.05	$984.54
8	$1,880.34	$531.95	$1,348.39	$19,647.10	$912.65
9	$1,880.34	$571.66	$1,308.68	$19,075.44	$843.59
10	$1,880.34	$614.33	$1,266.01	$18,461.11	$777.22
11	$1,880.34	$660.19	$1,220.15	$17,800.92	$713.40
12	$1,880.34	$709.47	$1,170.87	$17,091.45	$651.99
13	$1,880.34	$762.43	$1,117.91	$16,329.01	$592.85
14	$1,880.34	$819.35	$1,061.00	$15,509.67	$535.88
15	$1,880.34	$880.51	$999.84	$14,629.16	$480.94
16	$1,880.34	$946.24	$934.11	$13,682.93	$427.93
17	$1,880.34	$1,016.87	$863.47	$12,666.06	$376.73
18	$1,880.34	$1,092.78	$787.57	$11,573.28	$327.25
19	$1,880.34	$1,174.35	$705.99	$10,398.93	$279.39
20	$1,880.34	$1,262.01	$618.33	$9,136.92	$233.04
21	$1,880.34	$1,356.22	$524.12	$7,780.70	$188.13
22	$1,880.34	$1,457.46	$422.88	$6,323.24	$144.56
23	$1,880.34	$1,566.25	$314.09	$4,756.99	$102.26
24	$1,880.34	$1,683.17	$197.17	$3,073.82	$61.14
25	$1,880.34	$1,808.82	$71.53	$1,265.00	$21.12
Total	$47,008.57	$21,735.00	$25,273.57		$16,251.01

Table 1 shows that the electricity usage for the customer whose data is analyzed in Table 3 is 8206 kWh. Previous works have noted that the amount of electricity that is produced from solar panels decreases with the years. Assuming the solar panel is able to generate this amount of electricity for a 25-year period (neglecting the depreciation in the efficiency with time), the amount of electricity from the solar panels will be 25 × 8206 kWh = 205,150 kWh. The total cost of the loan is $ 47,008.57 (including interest payment).

$$The\ cost\ of\ electricity\ to\ consumer = \frac{Total\ cost\ of\ the\ loan\ for\ solar\ panels}{Amount\ of\ electricity\ to\ be\ produced\ by\ the\ solar\ panel}$$

In the above situation,

$$The\ cost\ of\ electricity\ to\ consumer\ = \frac{\$47{,}008.57}{205{,}150 kWh} = 0.229\ \$/kWh$$

If desired, the total cost of the loan may also be calculated by adding the present worth of interest payment to the principal payment. The above illustration does not include the cost of distribution/transmission that the utility companies will charge to supply energy during the hours and months when the solar panel alone is not able to meet the electricity demand of the household. Canada Greener Homes Loan program by Natural Resources Canada [34] offers an interest-free loan (from $5,000 to $40,000) for 10 years to help Canadians homes be more energy efficient. Hence, if the household meets the eligibility requirement, then the cost of the loan will be greatly reduced.

If the above scenario is for a no-interest loan, the cost of electricity from solar panels will be

$$The\ cost\ of\ electricity\ to\ consumer\ = \frac{\$21{,}735.00}{205{,}150kWh} = 0.106\ \$/kWh$$

Note that the solar panels may still generate electricity after a 25-year period, in that case, the cost per kWh of electricity that is generated from solar panels will be reduced (assuming there is no significant associated maintenance cost for the solar power system). Table 4 shows the average cost of electricity for the five residential customers. The most cost-effective system is the one that gives the lowest life-cycle cost or highest life-cycle savings [29]. Hence, when comparing the cost of electricity from solar panels with the cost of electricity from the community grid, in addition to the direct physical cost of owning the solar energy systems, further research is recommended on indirect cost savings such as reduction in health-related expenses as a result of the expected reduction in illnesses that are related to air pollution.

Table 4. Average cost of electricity ($/kWh) for the residential customers.

Customer	Average cost of electricity ($/kWh), for a 1-year period (2022–2023)
Customer 1	$0.07
Customer 2	$0.17
Customer 3	$0.08
Customer 4	$0.07
Customer 5	$0.07

Note that the electricity bills that were used in the study were for the years 2022–2023. However, it appears the cost of electricity from the grid has increased in recent times. Continuous study on the economic attractiveness of renewable energy systems is recommended to ensure that renewable energy systems can be maintained at an attractive level to encourage its use as a tool to better manage non-renewable energy systems for present and future generations.

3.2. Impact of varied interest rates on solar investment

Interest rate is an important economic factor that has a tendency to have a high impact on the economic feasibility of solar energy systems for micro-electricity generation through rooftop PV systems. In terms of the monthly economic impacts on the customer, the total amount to be paid by the customer, and the number of years for cumulative solar savings to become positive, Table 5 and Figure 1 indicate how the economic feasibility of solar investment can be significantly affected by variations in interest rates.

Table 5. Impact of varied interest rates on the economic outlook for solar investments.

Interest rate (%)	Monthly payments on amortization period of 25 years ($)	Total amount to be paid by the customer for 25-year amortization period ($)	Total amount that goes towards interest payment ($)	Principal loan amount ($)	Number of years for solar savings to become positive	Number of years for cumulative solar savings to become positive.
1	$81.92	$ 24,575.16	$2,840.16	$21,735.00	14	24
2	$92.14	$27,642.54	$5,907.54	$21,735.00	16	26
3	$103.11	$30,933.26	$9,198.26	$21,735.00	18	28
4	$114.80	$34,440.84	$12,705.84	$21,735.00	19	29
5	$127.19	$38,156.53	$16,421.53	$21,735.00	21	30
6	$140.23	$42,069.60	$20,334.60	$21,735.00	22	32
7	$153.89	$46,167.85	$24,432.85	$21,735.00	24	33
7.2	$156.70	$47,008.57	$25,273.57	$21,735.00	24	33

Table 5 shows that the total amount to be paid by the customer for a 25-year amortization period increases significantly with interest rates. At a 7.2% interest rate, the amount to be paid by the customer is more than doubled. Note that for the illustration in Table 5, the principal loan amount is $21,735.00. Figure 1 shows how the monthly payment is expected to increase with the increase in the interest rates. The increase in the monthly payment for a 25-year amortization period increased more than 90% when the interest rate is increased from 1% to 7.2%.

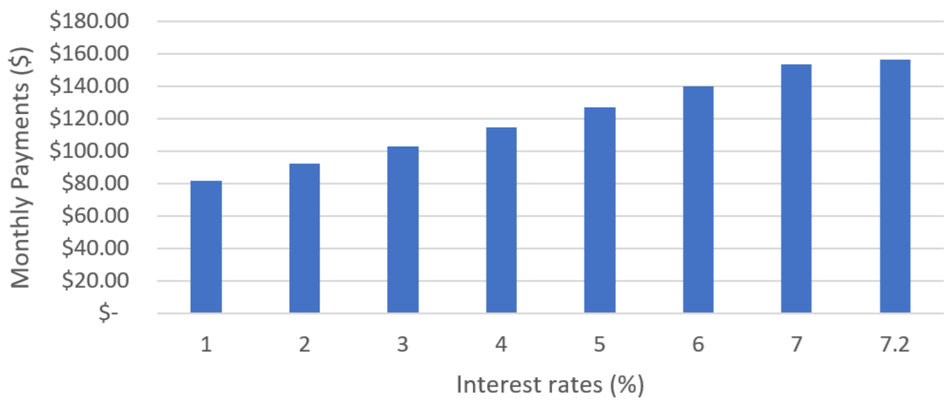

Figure 1. Monthly payments with varied interest rates on an amortization period of 25 years on a principal loan amount of $21,735.

Maintenance of zero interest or charging a low amount as administrative fees for renewable energy systems can help ensure that people in various communities will not feel much economic burden for investment in solar energy or other renewable energy systems as compared with a policy that allows renewable energy investments to be severely impacted by increased interest rates. Policy decisions that allow the effect of increased interest rates to impact the total cost of solar energy investments will constitute roadblocks to the attractiveness of solar energy systems. Hence, to improve the economic attractiveness of rooftop solar harvesting, it is desirable to maintain policies that shield solar energy investments from the impact of increasing interest rates. High interest on loans means that the annual payment of the loans will increase if the number of years to repay the loans is fixed and the loan is on a variable-interest policy. With higher interest on loans with variable rate policies, consumers' periodic payments will increase, meaning that people will have less money to afford essential commodities. Depending on individual salaries, the standard of living of people in the community may reduce when they are not able to afford essential things like good food for a balanced diet, good housing, adequate access to recreational facilities, funds for team sports, etc.

For the low-income, an increase in interest rates that results in an increase in monthly payments may result in significant economic stress for the families. Sometimes, it is said that increasing interest rates is a measure to curtail inflation. However, it is important to have policies that ensure that increasing interest rates do not harm people in the community in general. There is a need to ensure that adequate attention is given to other factors that may affect the prices of goods and commodities. For example, the natural law of demand and supply indicates that when the supply is less than the demand, the price may increase. Hence, it is important to ensure a good balance for various aspects of the economy including housing, energy, transportation, etc. In terms of the laws of demand and supply, every government should ensure that measures to monitor the level of demand and supply for every essential commodity exist to avoid unnecessary increases in prices. In terms of human factors such as price gouging that may result in unnecessary increases in the prices of goods and services, there is a need for adequate regulations to ensure that the prices of goods and commodities are not increased unnecessarily. Further research is recommended on how hardship can be minimized for medium and low-income people in the community during periods of high interest rates. Further study is also recommended on how the laws of demand and supply and adequate government policies can be used to control inflation rather than excessive focus on interest rates as a means to control inflation.

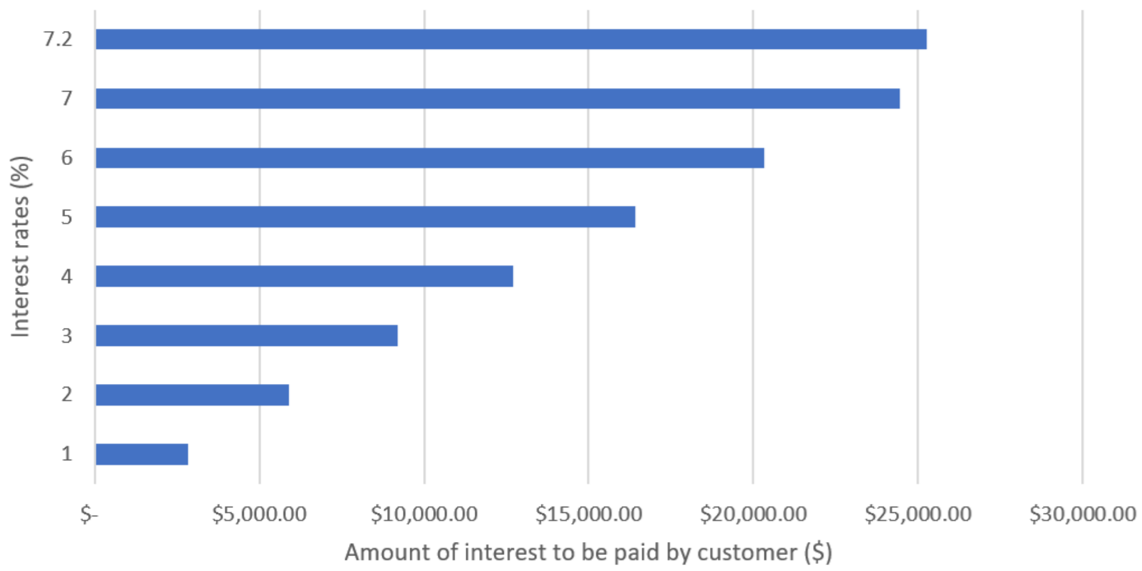

Figure 2. Impact of varied interest rates on total interest that is to be paid by the customer (principal loan amount 21,735, for 25 years).

Figure 2 also shows that the amount that will be paid as interest by the customer significantly increases as the interest rate rises from 1% to 7.2%. Although the present worth of the interest in 25 years at a rate of 5% discount rate is less than the total amount of interest to be paid by the customer in 25 years, the total amount paid on interest is still a sizeable sum of money. Hence, it is important to ensure that increasing interest rates does not severely impact renewable energy investments. It is fine to allow some administrative fees. Sometimes, government intervention may be needed in different places if the local manufacturers are not able to produce goods and commodities that are essential for daily living in a community. For example, some communities may benefit from government intervention to provide capital for the establishment of companies that manufacture materials for renewable energy systems on a large scale. Some government policies have shown that targeted policies can be applied to shield people from the impact of high interest. An example is Canada's Federal Greener Homes Loan Program which provides interest-free financing to help Canadians make their homes more energy-efficient and comfortable (up to $40,000) with a 10-year payback period [34]. Policies like this are expected to increase the economic attractiveness of renewable energy systems.

3.3. Effect of increased microgeneration capacity as measured by increased revenue on the economic attractiveness of solar energy systems for homeowners

Micro-generation capacity of solar energy from rooftops is the amount of electricity that each household is allowed to produce from solar panels on their rooftops. Table 6 shows an illustration of the effect of varied micro-generation capacity on the economic attractiveness of rooftop solar energy systems.

Table 6. Impact of varied micro-generation capacity of electricity from solar energy on the economic outlook for solar investments while keeping the interest rate at 1%.

Capacity for micro-generation of electricity from solar energy	Interest rate (%)	Number of years for solar savings to become positive	Number of years for cumulative solar savings to become positive
Micro-generation of electricity (from solar energy) limited to household needs	1	14	24
Two times increase in micro-generation of electricity by household	1	3	5
Three times increase in micro-generation of electricity by household	1	1	1

Table 6 above shows that increasing the microgeneration capacity of households increases the economic attractiveness of solar energy systems for households. At an interest rate of 1%, as the micro-electricity generation capacity increases (without increasing the electricity distribution/transmission fees and administrative fees), the number of years for the cumulative solar savings to become positive decreases rapidly. However, Figure 3 indicates that when the electricity distribution fee is increased in the same proportion as the micro-generation capacity, the number of years for cumulative solar savings to become positive does not reduce at an attractive rate as it was when the electricity distribution fee is not increased. This shows that the economic attractiveness of solar energy investments can be significantly affected by the amount that is charged as distribution/transmission fees for electricity that flows between the homeowners and the electricity grid in the community. Some other researchers [35] also reported that better economic satisfaction can be achieved from larger solar rooftop system sizes.

Irregular outlines and rooftop obstacles contribute to the challenge of manual PV packing [15]. This challenge can be mitigated by the adoption of rooftop solar systems that can be easily customized to various shapes and sizes without a reduction in their efficiency. A previous work [36] proposed an optimal planning strategy that can be used for municipal-scale distributed PV systems in high-density cities. One of the previous works that was cited mentioned the issue of uneven solar energy intensity distribution on an individual rooftop. Although this could be a concern, the variability of the intensity of solar energy at various points is a fact that should be accepted in planning for solar energy. To address the economic competitiveness in the production of solar PV system materials, training students in solar PV production and installation would be a beneficial addition to the educational curriculum at various levels of education (e.g., primary, secondary, colleges, etc.) in different parts of the globe. Further research on the reduction of the production and installation costs for solar PV systems will be commendable. Although accurate rooftop solar potential characterization is important, it is challenging [14]. A scholar [37] demonstrated how solar power that can be generated from rooftops will vary with various factors such as roof pitch/angle of tilt of the solar panels, azimuth, etc.

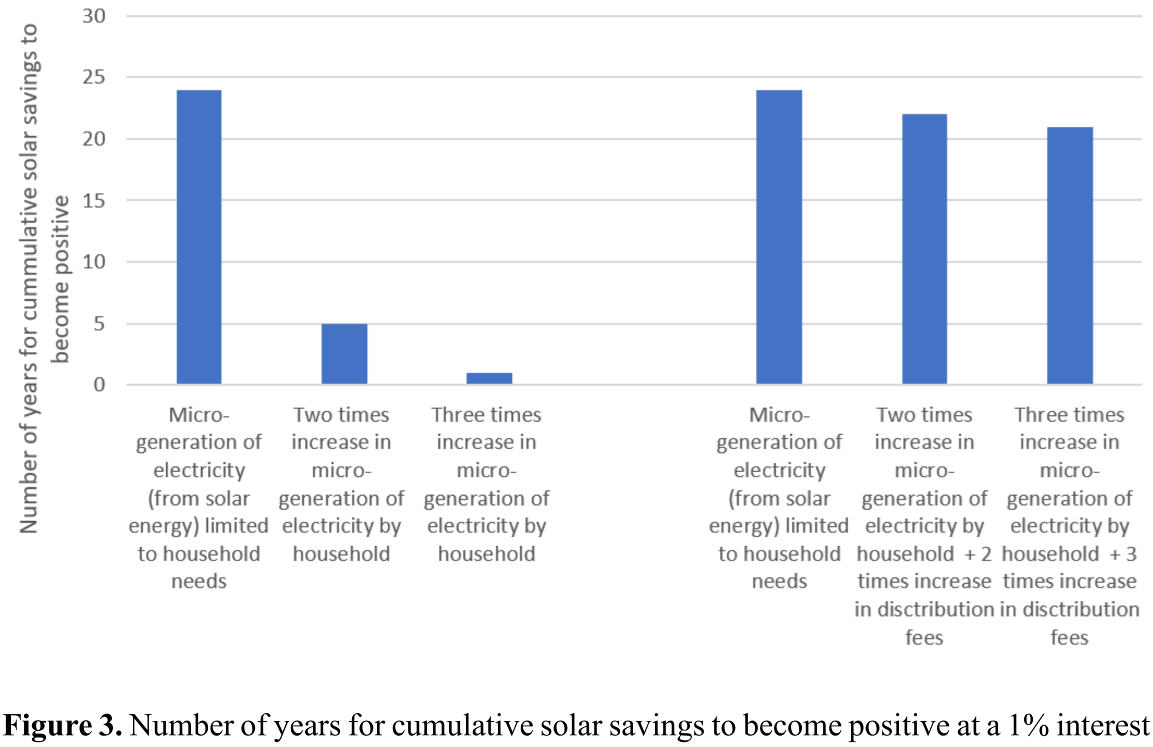

Figure 3. Number of years for cumulative solar savings to become positive at a 1% interest rate (considering the impact of the increase in electricity distribution fees).

Efforts to keep the distribution/transmission fees as low as possible will help increase the economic attractiveness of solar energy systems. Under the given illustration, when the micro-generation capacity of the solar energy systems is doubled, and the distribution fees are increased by the same degree, the number of years for solar savings to become positive increases from 3 to 13 years while the time for the cumulative solar savings to become positive increased from 5 to 22 years. When distribution fees increase by the same degree by 3 times, the number of years for solar savings to become positive increased from 1 to 12 years while the number of years for the cumulative solar savings to become positive increased from 1 to 21 years. This also indicates that the amount that is charged for distribution fees can have a significant impact on the economic profitability of solar energy investments for homeowners.

In Figure 4, while varying the capacity of micro-electricity generation from rooftops, the number of years for cumulative solar savings to become positive with varying interest rates (1%, 3%, 5%, and 7.2%) was evaluated (without increasing the electricity distribution fees). However, the effect of inflation was allowed on the cost of electricity distribution, administrative fees, and microgeneration credits.

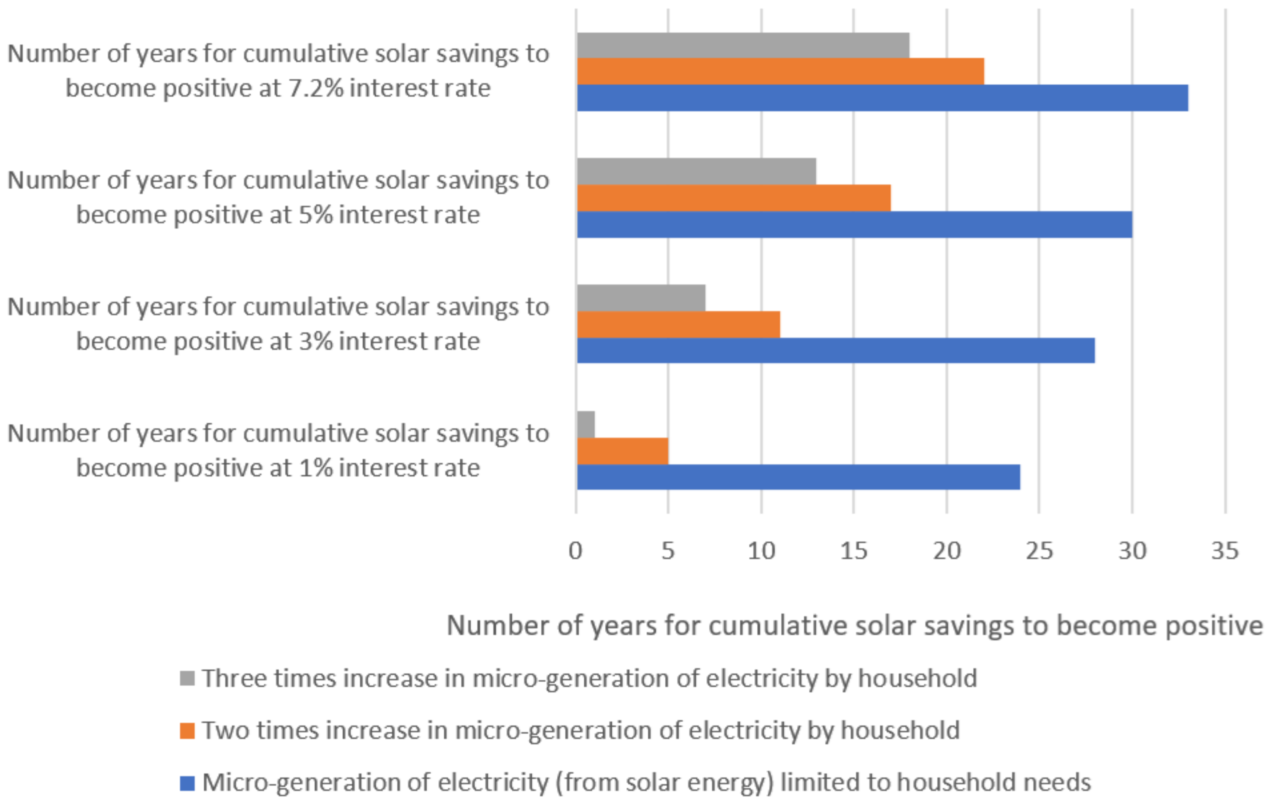

Figure 4. Comparison of the effect of the increase in micro-generation capacity of households on the time for cumulative solar savings to become positive while varying interest rates (without an increase in the transmission fees).

On their website, an organization [38] noted that Alberta Utilities Commission Rule 024 states that annual generation of electricity by Micro generators (individual generators) is not permitted to exceed 100% of their annual consumption. Figure 4 indicates that the financial attractiveness of solar panels by households can be increased by increasing the allowable micro-electricity generation capacity. As in the previous illustration, the number of years for the cumulative solar savings to become positive reduces with an increase in the micro-electricity generation capacity by the household. However, an increase in interest rate showed a significant impact on the financial attractiveness of investment in solar energy systems. i.e., As interest rates increase, the number of years for solar savings and the cumulative solar savings to become positive increases. This will yield a reduced economic attractiveness for solar energy investments. The impact of high interest rates is not desirable for solar energy investments. The effect of the increase in electricity microgeneration potential for households is measured by the increase in revenue. The quote that was given by the solar contractor was scaled up in the same magnitude that the revenue for the microgeneration of electricity was scaled up. Figures 5 and 6 show some cases in which the roof areas of some buildings are under-utilized for solar power harvesting. These pictures were taken during a walk-through of some neighbourhoods in a city.

Figure 5. Illustration of underutilized portions of rooftops that can be used for solar energy generation.

Figures 5 and 6 show that there are opportunities to increase the amount of solar power generation from the rooftops of different households. When adequately applied (without allowing transmission fees to overshadow the economic benefits), solar panels can become more economically attractive to homeowners. With this, the world will be moving closer to the goal of sustainable management of non-renewable resources for present and future generations. The world will also benefit from improved air quality when electricity is generated from less polluting sources. In a study on the technical and economic study of PVT coverage on an integrated building-solar-heat pump system, some researchers [23] also reported that the result of a thermal dynamic software (TRNSYS) that was used to model the annual coverage of the photovoltaic/thermal module through solar fraction determination indicated that with an increase in photovoltaic/thermal area, there is a significant increase in solar electrical fraction.

Figure 6. Useable spaces on roof areas for solar energy generation.

3.4. Effect of incentives on the economic attractiveness of solar energy systems for homeowners

Table 7 shows a comparison of the effect of varied levels of incentives on the economic outlook for solar investments at a 1% interest rate. As the level (amount) of incentives increases, the total amount of interest that is paid by the customer reduces. This can generate an economic attractiveness for the installation of solar panels. However, previous results above showed that when renewable energy investments are not shielded from the negative impacts of increased interest rates, an increase in interest rates can have an adverse impact on the economic attractiveness of solar panels.

Table 7. Effect of varied incentives on the economic outlook for solar investments at a 1% interest rate.

Interest rate (%)	Solar energy incentive ($)	Total amount of interest to be paid by the customer	Number of years for solar savings to become positive	Number of years for cumulative solar savings to become positive.
1	0	$2,840.16	14	24
1	2000	$2,604.95	13	22
1	4000	$2,369.74	11	19
1	6000	$2,134.53	10	17

Figure 7 also shows that the total amount of interest to be paid by the customer reduces with an increase in the incentives for solar installations. However, the increase in the tax overshadows the positive effect of the incentives.

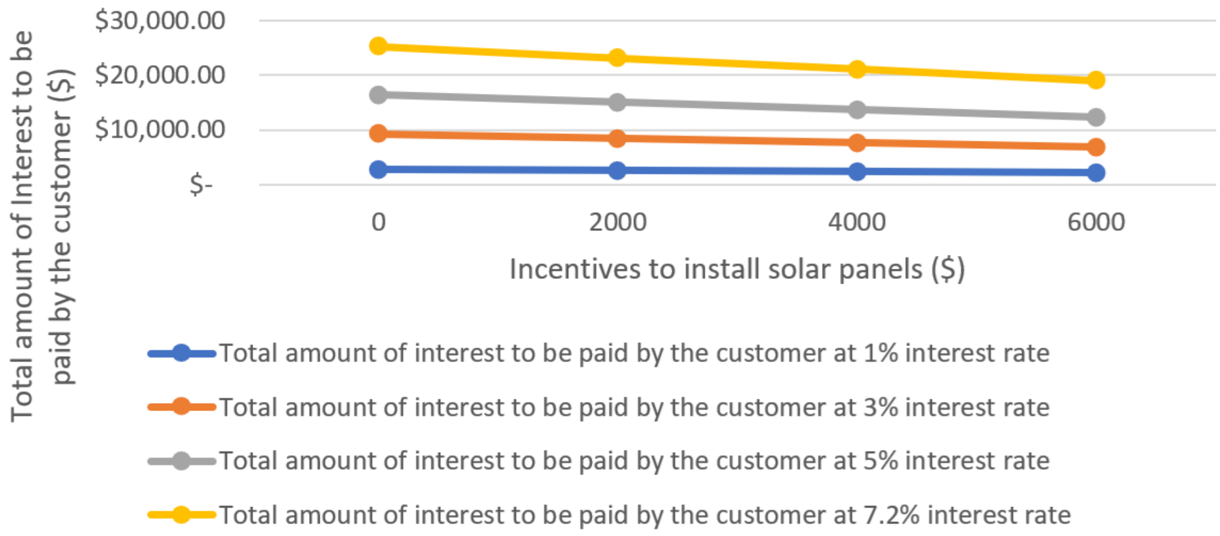

Figure 7. Effect of solar incentives on the total amount of interest to be paid by consumers.

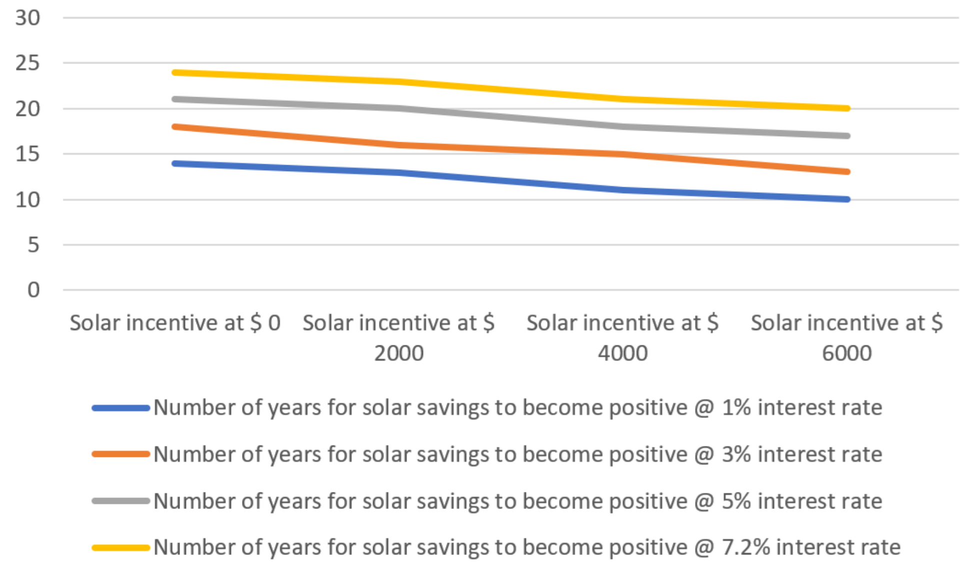

Figure 8. Comparison of the number of years for solar savings to become positive at varied interest rates and different levels of incentives.

Figure 8 indicates that the number of years for the solar savings to become positive reduces with the amount of incentives that are applied but this is overshadowed by the impact of increase in interest rates on solar energy systems. i.e., higher interest rates can reduce the expected effect of the incentive in the long term. Hence, it is important to ensure that adequate measures are taken to ensure that increased interest rates do not nullify the expected attractiveness of other incentives for solar panels.

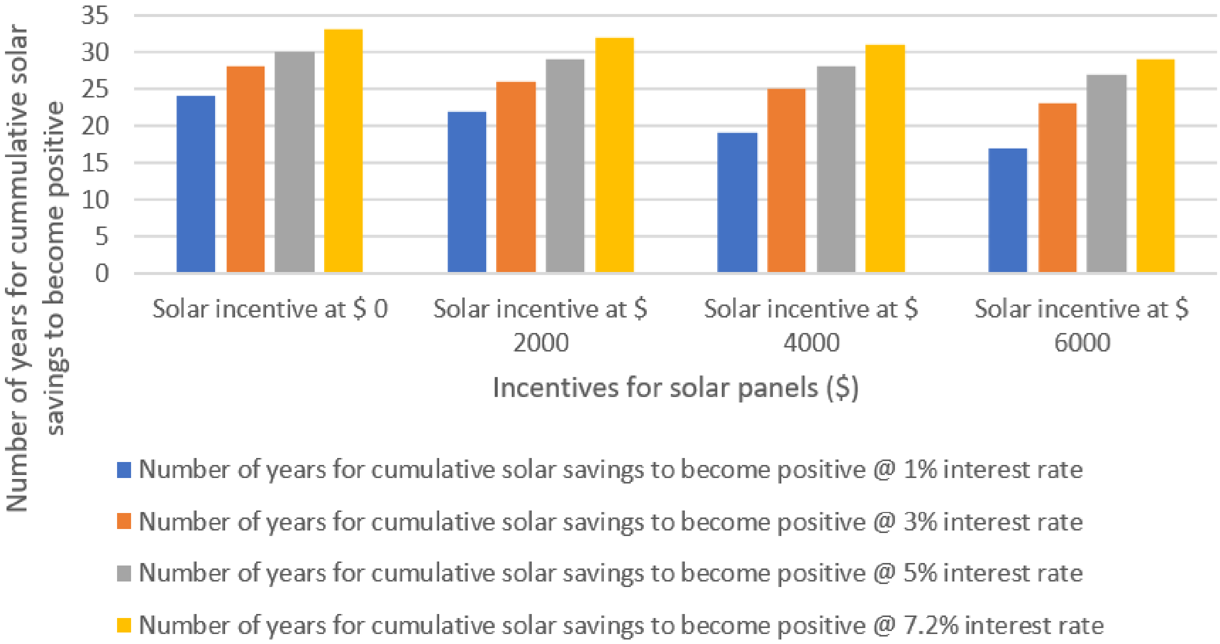

Figure 9. Comparison of the number of years for cumulative solar savings to become positive at varied interest rates and different levels of incentives.

Government subsidies are still needed for solar PV systems to be competitive with other forms of energy [5]. However, similar to the trend in Figure 8, Figure 9 also showed that increased interest rates overshadow the benefits of the specified incentives for solar panels.

3.5. Evaluation of the impact of incentives, variations in interest rates, and micro-generation potential on the economic attractiveness of rooftop solar energy systems

Among the three factors (interest rates, incentives, and increased micro-generation capacity) that were evaluated, Figure 10 indicated that increasing the amount of electricity that is allowed to be generated from rooftops will result in the highest economic attractiveness for end-users. This is also expected to move the world closer to the goal of sustainable management of non-renewable resources for present and future generations.

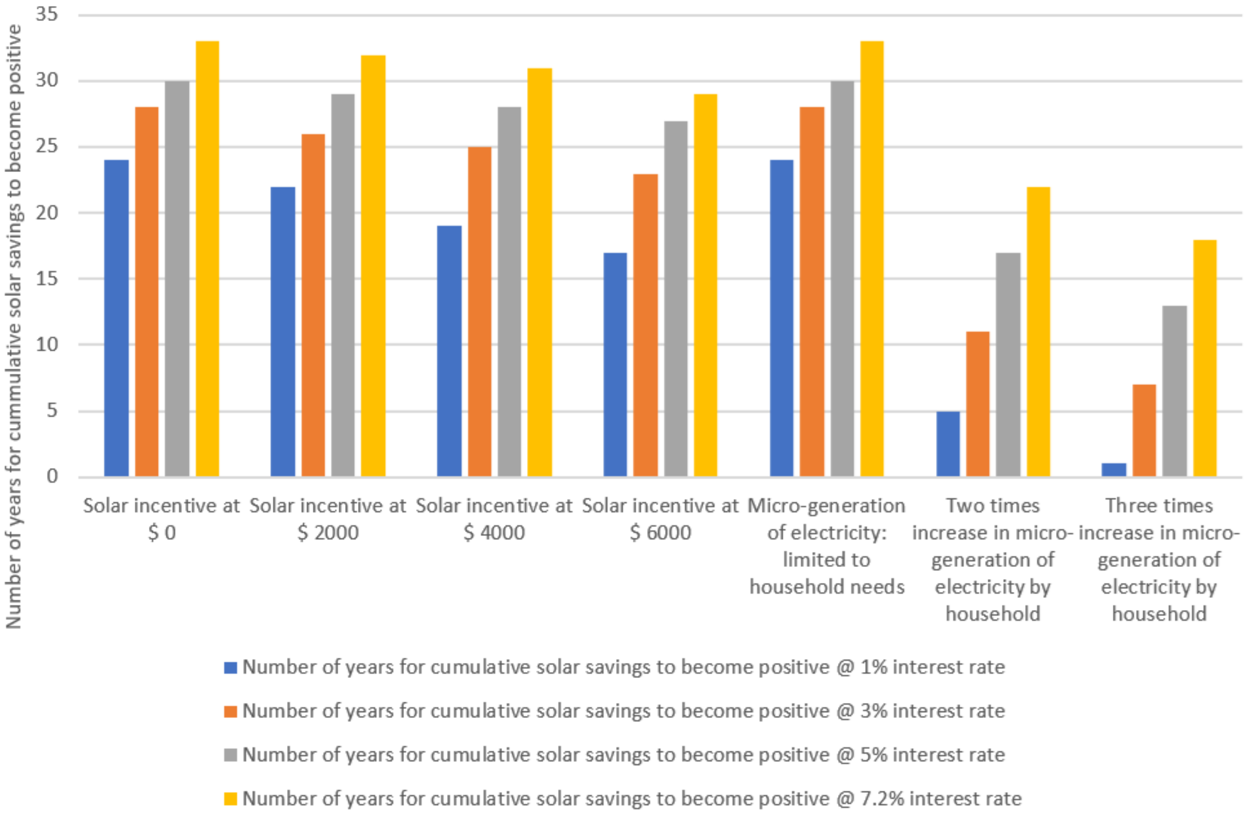

Figure 10. Comparison of the impact of incentives, interest rates, and capacity for micro-generation policy on the economic attractiveness of rooftop solar energy systems.

Given the above results, this study recommends the encouragement of policies that allow for a maximization of rooftop spaces for solar energy generation in residential and commercial buildings. With the aid of bi-directional meters, the amount of electricity that flows to and from the grid to each household can be measured. If desired, excess energy that is sold to the community grid may be counted as taxable income after the panels have exceeded the payback time on investments. However, such tax should be monitored and carefully designed in a way that does not significantly reduce the economic attractiveness of rooftop solar harvesting.

4. Discussion

4.1. Expected GHG emission savings from solar panels

Various previous works have mentioned the environmental benefits of solar energy systems [39–47]. Some researchers [40] cited previous works that indicated that the GHG emissions of amorphous solar PV systems range from 15.6 to 50 $gCO_2/kWhe$. The locations for the studies referenced for amorphous solar PV systems are China, the US, and the Netherlands. The GHG emissions for mono-crystalline solar PV systems range from 44 to 280 gCO_2/kWh_e. The locations for the studies referenced for monocrystalline solar PV systems are the UK, Netherlands, India, Japan, Singapore and the US. The GHG emissions for poly-crystalline solar PV systems range from 9.4 to 104 gCO_2/kWh_e. The locations for the studies referenced for polycrystalline solar PV systems are China, Italy, Japan, the US, and

Greece. Based on information on the life cycle energy components of mono-crystalline PV panels that was adopted from the literature and the final yield of monitored PV systems, another study [45] reported that the average GHG emission for PV systems is 49.33 gCO_2 eq/kWh. The average GHG emission for PV systems that were mentioned in [45] was selected for the illustration below because that study was done in the same country as the data that is under evaluation in this study.

4.1.1. Illustration of GHG emission reduction from a policy that supports an increase in micro-generation capacity of electricity from households

With an electricity use of 8,206 kWh for the year for customer 2, allowing the customer to increase the amount of electricity that is generated from photovoltaics on rooftops by 2 times what the household can use in a year will mean that the household can generate an additional 8,206 kWh extra electricity per year. If customer 2 is allowed to generate thrice the amount of electricity that the family can use on an annual basis, this means that the household can generate 16,412 kWh of electricity extra.

Using the average GHG emissions for 0.59 $kgCO_2eq$/kWh for a region for year 2020 to estimate the GHG emissions for electricity from the grid (as mentioned in previous works [48,49]) and 0.04933 $KgCO_2$ eq/kWh as average GHG emissions from PV systems as mentioned in the study by [45], the annual GHG savings by increasing the amount of electricity to be generated from rooftop PV systems by 2-folds and 3folds in the illustration above will be as projected below.

4.1.2. GHG emission savings for a 2-fold increase in micro-generation capacity by the household

This is estimated by subtracting the expected GHG emissions per kWh of electricity from PV systems on a lifecycle basis from the GHG emission per kWh of electricity from the grid. i.e.,

$(0.59 \frac{kgCO_2eq}{kWh} \times 8206\ kWh) - (0.04933 \frac{KgCO_2eq}{kWh} \times 8206\ kWh) = 4841.54\ kgCO_2eq - 404.80\ kgCO_2eq = 4436.74\ kgCO_2eq$ per annum (savings in GHG emission) at a 100% increase in the micro-generation capacity of the household.

If this level of savings of GHG emissions is maintained for 25 years, this is expected to result in $25 \times 4{,}436.74 = 110{,}918.45\ kgCO_2eq$ savings in GHG emissions for a 25-year period for which some PV systems may be under warranty.

4.1.3. GHG emission savings for a 3-fold increase in micro-generation capacity by the household

Similar to the method described above, a 3-fold increase in micro-generation from the household means that an additional 16,412 kWh of electricity can be generated by the household.

$(0.59 \frac{kgCO_2eq}{kWh} \times 16{,}412\ kWh) - (0.04933 \frac{KgCO_2eq}{kWh} \times 16{,}412\ kWh) = 9683.08\ kgCO_2eq - 809.60\ kgCO_2eq = 8873.48\ kgCO2eq$ savings in GHG emission for the year at a 3-fold increase in the micro-generation capacity of the household.

If this level of savings of GHG emissions is maintained for 25 years, this is expected to result in $25 \times 8873.48 = 224837\ kgCO_2eq$ savings in GHG emissions for a 25-year period for which some PV systems may be under warranty.

Note that these projected savings in GHG emissions may be reduced as technological innovations to improve the emissions from the electricity grid are implemented. The GHG emissions coefficient from the grid above is for illustration purposes only. The GHG emission coefficient presented above is for the year 2020 while the electricity usage that is evaluated is between the years 2022 to 2023.

Policy upgrades to allow for a maximization of the amount of solar energy that each household can harvest from the electricity grid will not only help create economic attractiveness for solar energy systems for individual households and industries, it will also help in the effort to reduce the concern about GHG emissions. In addition, it can be a means to boost the economic well-being of people in various communities. With the increase in the micro-generation capacity of electricity by households comes a question of how the excess electricity that is generated can be used.

4.1.3.1 How can excess solar energy that is generated by households be used?

Excess solar energy can be shared with other people in the community either through a direct sale to the energy utility companies or through community energy-sharing programs that may come in different categories. The community share solar system is a system in which the solar energy that is generated in a community can be shared by members of that community. Although the community share solar system has reached its maturity, lack of attention to the socio-political aspect and especially the institutional and regulatory aspects are barriers to the emergence of the community solar system and its potential position as a leading energy system [4]. Excess energy that is produced may also be stored for use at later times or exported to other communities that may need it. The illustrations provided in this study indicated that there is room for improvement in the amount of solar energy that is allowed to be harvested from rooftops in different places. Incentives have the potential to create economic attractiveness for people to install solar energy systems. However, an increase in the amount of solar energy that can be harvested from rooftops will generate more economic attractiveness for solar energy and at the same time help in moving the world closer to the goal of reducing GHG emissions in various communities. This study recommends further exploration of means to harvest renewable energy resources to allow for sustainable management of non-renewable energy resources for present and future generations.

5. Conclusions

This study reviews the economic attractiveness of solar energy systems with multiple variables. The impact of varied amount of interest rates, micro-generation capacity for electricity produced from PV panels, and incentives were evaluated. The result of the study showed that harvesting solar energy from rooftops can be economically feasible. However, there is a need to focus attention on the variables that can increase the economic attractiveness of solar energy while ensuring that adequate strategies are in place to ensure that factors that can reduce the economic attractiveness of renewable energy systems are duly mitigated. Among other things, the study found that:

(1) An increase in the micro-generation capacity of households (without increasing the transmission and distribution fees) generated the highest economic attractiveness for solar energy systems.

(2) Comparative increase in the electricity distribution fees reduces the economic attractiveness that is expected from an increase in the micro-generation capacity from individual rooftops. Hence, it is recommended that adequate policies should be made to ensure that the expected economic

attractiveness from an increase in the microgeneration capacity from individual buildings is not overshadowed by an increase in the electricity transmission fees.

(3) Although government subsidies and measures to reduce the negative impact of high interest rates can be a means to increase the economic attractiveness of solar energy systems, increasing the micro-generation capacity without increasing the electricity transmission fees shows the highest positive effect on the economic attractiveness of solar energy systems.

This study also recommends that policy updates to encourage the increase in micro-generation capacity of electricity from rooftops of individual households and industries be given a higher consideration to improve the economic attractiveness of solar PV systems while creating better paths to manage non-renewable energy resources for present and future generations. It is recommended that increased micro-electricity generation be accompanied by adequate community sharing programs and proper system planning and integration to ensure that the entire community has reliable backup during periods when electricity supply from solar energy systems is low. The practical implication of these recommendations for policymakers and the global community is that maximizing solar PV energy systems will move the world closer to the goal of sustainable management of non-renewable energy resources while reducing GHG emissions in the global community.

When the goal is to achieve a significant reduction in GHG emissions, associated policies should support the maximization of opportunities to reduce GHG emissions. This includes policy updates to remove roadblocks for the maximization of the available roof area of the building for the generation of solar power (for property owners that maximize their roof space for solar energy harvesting). Allowing the excess energy that is generated from microgrids to contribute to the electricity from the grid means that the overall GHG emissions from electricity in the community can be significantly reduced when a significant number of people maximize the solar power generation potential from their rooftops. In the effort to increase the use of renewable energy to supplement 'non-renewable' energy resources, there is a need for policy updates in different places to increase the attractiveness of PV systems. This includes a careful design of policies that reduce the payback time for solar energy systems for residential and commercial buildings. The findings of this study can be helpful for such strategy development to increase the economic attractiveness of rooftop solar energy harvesting. Efforts to reduce the total cost (material and labor) to have a PV system will go a long way to reduce the payback time while creating more basis for attractiveness for solar energy systems. When a customer notifies the utility company of the intent to maximize the roof space with solar generation potential, this customer becomes a partner in the effort to reduce the greenhouse gas emissions from the electricity grid. The utility company may adjust the amount of power that is produced and supplied to the grid from the utility company accordingly. This study recommends that property owners who maximize their rooftop spaces for solar harvesting should not be denied the opportunity to connect to the community grid. Rather efficient sharing of such renewable energy harvested to other members of the community should be encouraged.

Adequate efforts to ensure that the material production cost, purchase, and installation costs for solar energy systems are maintained at a reasonable level are recommended. The impact of increased interest rates overshadows the economic attractiveness of incentives at the incentive levels that were evaluated. Hence, this study also recommends that adequate measures to shield renewable energy systems from the impact of high interest rates be given higher consideration (in places where it is not already a norm) to increase the economic attractiveness of renewable energy systems.

5.1. Further research directions

(1) Continuous study on the economic feasibility of renewable energy systems is recommended to ensure that high economic factors such as high interest rates, utility distribution fees, bottlenecks from local policies, etc. do not constitute a hindrance to a reasonable adoption of renewable energy systems.

(2) Further studies on how to reduce the ownership cost of solar energy systems is also recommended.

(3) Further studies on increased awareness of the benefits of rooftop PV systems and how to increase PV production capacity within various communities globally is recommended.

(4) In the effort to develop more economically friendly solar PV systems, pilot studies on the benefits of inclusion of training on PV system production and installation in primary, secondary and college educational programs are recommended.

(5) Further study is recommended on best measures to ensure that varying weather conditions do not have significant negative impacts on the degradation rates of solar panels.

(6) Further study on the minimization of maintenance costs of solar PV systems while extending their lifespan is recommended.

5.2. Study limitations

Changes in different variables in economic analysis can result in a change in the result. For example, a change in the cost of solar energy systems will affect the time that it will take the solar savings to become positive. However, the methods that were described in this study can be used to evaluate the impact of multiple variables on the economic outlook of solar investments. If solar power will be more attractive to end-users, it is recommended that adequate attention be paid to the reduction of the cost of purchase and installation of solar energy systems. Reduction in investment cost for solar energy systems is expected to result in a reduction in the payback time for consumers.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declares no conflict of interest.

Author contributions

The project conception, design, data acquisition, analysis, evaluation and discussion of the results was performed by the Author (Adekunle Mofolasayo).

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