Consumption Patterns in the Residential Electricity Market; a Decision Making Tool

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Abstract

Electricity consumption patterns are changing globally. This is in part due to the emergence of the electricity prosumer, where an electricity customer is also generating electricity, mostly from rooftop photovoltaic (PV) installations.

This study introduces a computerized multi-criteria decision support tool for policy makers based on agent-based modeling (ABM) that mimics the installation patterns of these rooftop PV installations by households over time under different conditions. Input to the tool is provided by the results of an extensive online survey with residential electricity customers, conducted in 2018 aimed at understanding the drivers for household investment in rooftop PV, as well as workshops with distribution utilities held in 2019.

Additional inputs to this tool includes; rising electricity tariffs; changes in electricity tariff structures; the falling cost of rooftop PV systems; municipal regulations; national regulations; power supply interruptions and; punitive measures for unregistered and non-compliant PV systems.

The tool measures how, and to what extent, individual choices pertaining to the installations of residential rooftop PV are both influenced by the state of the system and influences the state of the system in turn.

Keywords: Rooftop photovoltaic systems, electricity tariffs, net metering, feed-in tariffs, grid defection, agent-based modeling, multi-criteria decision making.

1. Introduction

The worldwide increase in installations of rooftop solar photovoltaic systems (PV) (IRENA, 2016; IEA, 2018; REN21, 2019), as evident in Figure 1, is changing the way that households consume electricity. The rising cost of electricity, the falling cost of PV technologies (see Figure 2), and an increased awareness of the need to reduce consumption of electricity generated from the burning of fossil fuels, are all motivating factors for this increase. These trends are also seen in South Africa (see Figures 3 and 4), where continuing power failures further spurs on investments in rooftop PV. Although the benefits of rooftop PV is recognized, the increased penetration might pose both a risk to the financial viability of electricity utilities and a technical risk to grid operators, especially if the systems are not installed according to regulations. This risk is increased if the grid operator is unaware of the location of installations. In South Africa, only an estimated 25% of residential rooftop PV installations are registered at the local authority as required by law, with the remaining 75% of households opting to flaunt the law (Korsten *et al.*, 2017; SEA, 2017; Korsten, Kritzinger and Scholtz, 2018a, 2018b; Baker and Phillips, 2019; Zander *et al.*, 2019).

In the light of this, and in combination with other changes in electricity consumption, it becomes increasingly important to identify and understand the drivers of rooftop PV investment decision in the residential sector and the effect that these changes might have on the long term viability of utilities (van Niekerk, Kritzinger and Bekker, 2014; Montmasson-Clair, G; Kritzinger, K; Scholtz, L; Gulati, 2017; Coley *et al.*, 2018a; Korsten, Kritzinger and Scholtz, 2018a, 2018b). Not only do the expectations of electricity customers often not align with the expectations of the utility, but the expectations of utilities also differ depending on whether their mandate includes the local, regional or the national level.

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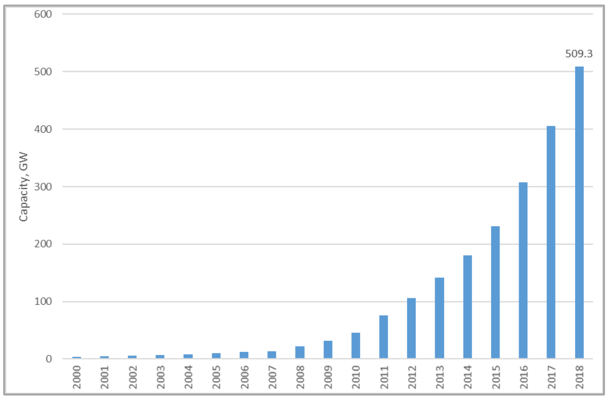


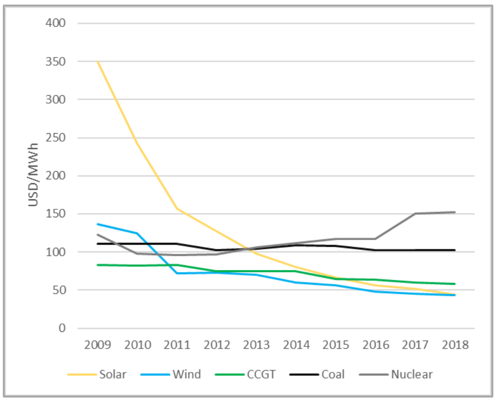
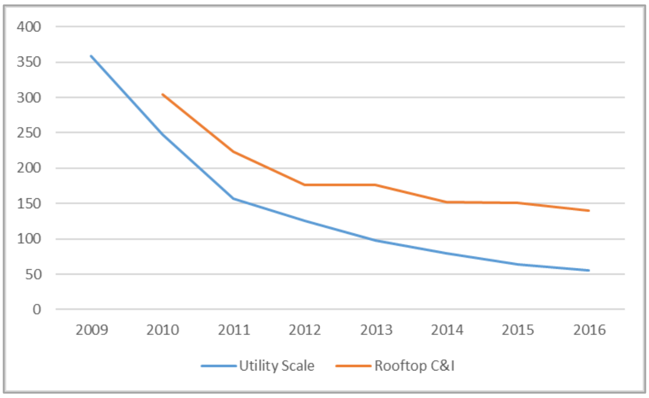


Figure 1 (left): Global total solar PV installed capacity 2000-2018 from (Schmela *et al.*, 2019) **and Figure 2 (right): Solar electricity generation cost in comparison to other power sources 2009 – 2018** (IEA, 2018; IRENA, 2019; REN21, 2019; Schmela *et al.*, 2019)



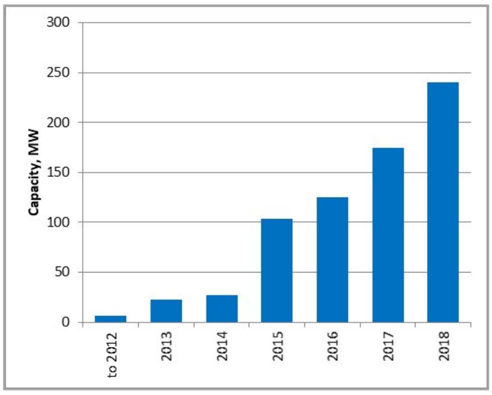


Figure 3 (left): LCOE for solar PV in South Africa, 2009 to 2016 for utility scale and for commercial and industrial (C&I) rooftop installations, in USD per MWh adapted from (DoE, 2018) **and Figure 4 (right): Additional rooftop PV installed in South Africa up to 2018 from** (AREP, 2019)

This study explains the rationale for building a computerized multi-criteria decision support tool for policy makers that mimics the installations of residential rooftop PV installations over time under different conditions.to better understand the complex interaction between consumer investment decisions and the tariffs charged by utilities. The aim of the tool is to visualize how changes in rooftop PV installations and different policy conditions mutually influence each other and the effect that these changes have on rooftop PV installations, policy changes as well as the electricity system. The computerized tool includes inputs that affect the system, such as; rising electricity tariffs; changes in electricity tariff structures; the falling cost of rooftop PV; municipal regulations; national regulations; power supply interruptions; and punitive measures for unregistered and non-compliant PV installations. The tool measures the effects these changes have on the system. Input to the tool is guided by the results of an extensive online survey with residential electricity customers, conducted in 2018 (Korsten, Kritzinger and Scholtz, 2018b) and workshops with distribution utilities held in 2019.

The paper is structured as follows; Section 2 provides the business case for rooftop PV from the household perspective; Section 3 continues with the business case for from the utility perspective; electricity tariffs are discussed in Section 4; Section 5 provides a general background on modeling techniques; Section 6 introduces the decision support tool and provides an analysis of the inputs needed; Section 7 provides preliminary results and concludes the work.

2. Rooftop PV: electricity customer perspective

Literature shows that internationally household decision to install rooftop PV is mostly influenced by financial, social, and environmental factors (Korsten, Kritzinger and Scholtz, 2018a). An electronic survey conducted in 2018 (Korsten, Kritzinger and Scholtz, 2018b), identified that currently South African households are mostly influenced by their ability to pay the capital cost as well as whether someone in their social group have already invested or whether they have been exposed to the technology in some other way. The survey also showed that the perception of high electricity tariffs and a low trust in the utility's ability to provide uninterrupted power supply influenced the investment decision. The business case for rooftop PV in combination with the findings of this survey is used to model future rooftop PV investment decisions for residential customers.

Although there are technical issues that the owners of rooftop PV have to manage, financial viability is a critical consideration for a new installation. There are three main factors that determine the financial viability for rooftop PV from the investor's perspective; the solar resource; the cost of the system and; the active energy charge part of the electricity tariff. Other less important factors include the expected lifespan of the installation, expected maintenance costs, replacement of parts and the degradation of the panels.

A simplified formula to calculate the viability of rooftop PV, is; P = C / (EC x SR), where P is the payback period in years, C is the capital cost per kWp, EC is the active energy charge per kWh and SR is the amount of electricity that the installation will generate per year per kWp installed. As an example, if SR = 1 500, EC = 0.08 USD per kWh and C = 1 400 USD / kWp, then the simple payback period is; 1 400 / (0.08 x 1 500) = 12 years.

While the solar resource and capital cost falls outside the ambit of control of the electricity utility, the tariff is determined by the utility, offering an opportunity for the utility to manipulate the rooftop PV installation market by either stimulating installations or by discouraging same. However, while an electricity tariff with high active energy charges might encourage the installation of rooftop PV, and might lead to a loss of income for the electricity utility, high fixed electricity charges might encourage customers to also disconnect from the utility and become self-sufficient, impacting even more severely on revenue flow. This is the dilemma that utilities face.

3. Rooftop PV: utility perspective

While rooftop PV installations on private buildings might impact on municipalities' finances, it will also impact on the technical operations of the electricity utility.

While the immediacy of electricity is not always evident for electricity consumers, it is the responsibility of the electricity transmission and distribution utilities to balance the generation and consumption of electricity in real time. The fluctuating electricity demand of individual consumers becomes reasonably predictable with aggregation, as consumers switch loads on and off independent of each other. Electricity utilities traditionally use this aggregated demand of customers in their network design, which means that the substation capacity is often much lower than the sum of the individual customer capacities feeding from that substation. This is especially true in residential areas. However, the integration of rooftop PV increases the complexity of the system by adding distributed and variable generation profiles to the pre-existing distributed and variable demand profiles. In addition, variable renewable energy generation only smooths out with aggregation over a large geographic area. It follows that if PV is installed on the roofs of all individual electricity customers up to their individual capacities, there will be a system overload when the sun is shining equally on these systems and the individual loads are not collectively high enough to absorb this generation. This can cause power quality problems and equipment damage (Mararakanye and Bekker, 2019). In addition, this could also pose a safety risk to utility employees working on these lines if the utility is not aware of the rooftop PV installations, and if it is configured to feed back into the grid during a power outage (Reinecke *et al.*, 2013).

When an electricity customer installs a rooftop PV system, this customer uses less electricity and consequently pay less to the utility. However, depending on the financial and technical structure of the utility, the cost to supply this customer might be independent of the amount of electricity used.

The immediacy of electricity generation and consumption also affects the cost. Electricity generated when there is a high demand is more useful and thus more valuable than electricity generated in a low demand period. If electricity generated by the PV is not used on site when generated, it will feed into the grid. Depending on the physical structure of the grid, and the load profiles of other loads in the vicinity, this electricity might be evacuated to other loads further away. The cost of these systems to the utility is thus also influenced by where the electricity is used and the resultant electricity losses as well as whether this electricity needs to be curtailed.

The tariff structure of these purchases will also influence the financial implication of these rooftop PV installations where utilities (i.e. distribution utilities), purchase electricity from other utilities (i.e. generation or transmission utilities). It goes without saying that the same financial implication as stated above for electricity customers purchasing less from the utility will be true for utilities purchasing from other utilities.

Interviews conducted by the researchers with key personnel from South African utilities indicate that they are well aware of both the financial and technical challenges that will flow from an increase in rooftop PV penetration. At the same time they are in support of, the need to move the power system away from fossil fuel generation and agree that rooftop PV has the ability to assist in this. They are all aware of the falling price of PV technologies and the increase in installations as well as how this would most probably only accelerate in the near future.

In order to address existing and future impacts on revenue, utilities are looking for ways to combat the anticipated problems. All utilities are investigating new tariff regimes that are fair and equitable and do not disproportionally benefit certain sectors. Some utilities are incorporating rooftop PV targets into their roadmaps towards sustainability and resilience whilst others are also investigating the ability of rooftop PV to solve capacity constraint problems for new developments.

All are concerned about the high number of unregistered rooftop PV systems in their jurisdiction. Respondents to the electronic survey who already have rooftop PV installed mostly (75%) indicated that they did not inform their utility of this installation. The utilities are mostly uncertain about how to address this as they are acutely aware of the likely repercussions from both a hard line approach and by overlooking this. In addition, most utilities are investigating own generation and the possibility of becoming more independent of the national grid, both for financial reasons and because they are of the view that Eskom will not be able to provide them with an uninterrupted power supply in the future, the exact same argument that the end-consumers make with regards to them. It is in this context that correct tariff setting becomes critical to avoid alienating prosumers and to ensure that they not only stay connected, but also that they register their systems with their respective utilities.

4. Electricity Tariffs

Globally, electricity is mostly sold at a predetermined rate, an "electricity tariff". These tariffs generally include; fees per time unit; capacity fees and active energy charges.

Fees per time unit are set fees charged per day, per week or per month and does not depend on the amount of electricity consumed.

Capacity fees are charged for both the maximum electrical capacity required by the customer, irrespective of whether this capacity is ever utilized and for the maximum capacity utilized. The first fee is usually charged as a "notified maximum demand" and penalties imposed should this be exceeded in a specific time period. Capacity fees are charged for the actual peak demand in specific time periods when the grid is under strain.

The **active energy charge** or "per kWh" charge, is the fee that people are most familiar with and can be charged at;

- a set rate per time period
- an inclining block tariff, where the price per unit goes up the more is used in a time period
- a declining block tariff, where the price per unit goes down the more is used in a time period
- a time-of-use (TOU) tariff, where units used in specific high demand time periods (either daily or seasonally or a combination of these) are charged differently
- a dynamic TOU tariff, where the cost per unit dynamically changes according to the demand for electricity at any specific time

Internationally, electricity tariffs differ according to the cost of electricity generation, transmission and distribution as well as the level of subsidization. The individual tariffs that electricity customers pay can also differ according to their customer class and / or usage patterns. It is quite common that high-income high-earning electricity customers cross-subsidize other low income / low earning electricity customers. In some countries, as is the case in South Arica, the income from electricity is also used to cross subsidize other municipal services.

Most utilities in developed countries bill electricity customers in an appropriate cost-reflective manner. An example of this is the declining block tariff structure, where the monthly kWh amount of active energy used is charged at a lower rate for high use customers, in line with their cost to the utility. However, in developing countries, income from electricity sales from high income customers are often used to cross subsidize electricity sales to low income customers. This is done using an inclining block tariff structure, where the active energy charge is increased for higher amounts of kWh used per month and is particularly popular with utilities for residential customers in South Africa. It is often justified as a tool to incentivize energy saving, energy efficient appliances and self-generation of electricity. This tariff structure also makes it more financially viable for the high electricity users (who usually costs the least per unit to supply with electricity) to install rooftop PV than for electricity customers who use less electricity.

Metering: Simple mechanical electricity meters, that are manually read (usually on a monthly basis) or simple electronic prepaid electricity meters (kWh "units" of electricity is paid for and loaded and the meter counts down the units as these are consumed), usually only measure the active energy used by the customer and do not capture the time of day that this energy is used nor the electrical capacity utilized. Most residential electricity customers worldwide have these simple meters installed and are only charged for a combination of fees per time unit, capacity fees and an active energy charge per kWh.

Larger electricity consumers, such as commercial and industrial (C&I) customers, usually have more sophisticated electricity meters installed and the utilities are able to charge these customers with more sophisticated tariffs. This tariff will more often include all three charges as described above.

Electricity tariffs in South Africa: In South Africa Eskom is the primary generator and seller of electricity. While some municipalities purchase electricity from Eskom and resell to their customers, in other areas customers are serviced directly by the distribution arm of Eskom. Accordingly, electricity customers either pay their electricity bill to Eskom or to their local municipality.

The residential electricity tariffs in South Africa are typically based on the ability to pay as well as on usage. Indigent electricity customers are on average provided with 40 to 100 free units of electricity per month and the units exceeding this is typically charged at an inclining block tariff. Higher income customers are often charged at an inclining block tariff. This results in low income electricity customers and customers who use a low amount of energy per month typically paying less per kWh than higher electricity users. To date the active energy charge part of the electricity charge makes up the largest part of the electricity bill for residential customers. However, this is starting to change, in part due to the uptake of rooftop PV, with some distributors introducing set charges to their residential customers. C&I electricity customers in South Africa are charged with a mix of capacity, time-based and active energy charges. Active energy charges makes up about 50% of the electricity bill for C&I customers. The aggregate electricity tariff from (Bradshaw and Martino, 2019) for a few key countries, including South Africa, can be seen in Figure 5.

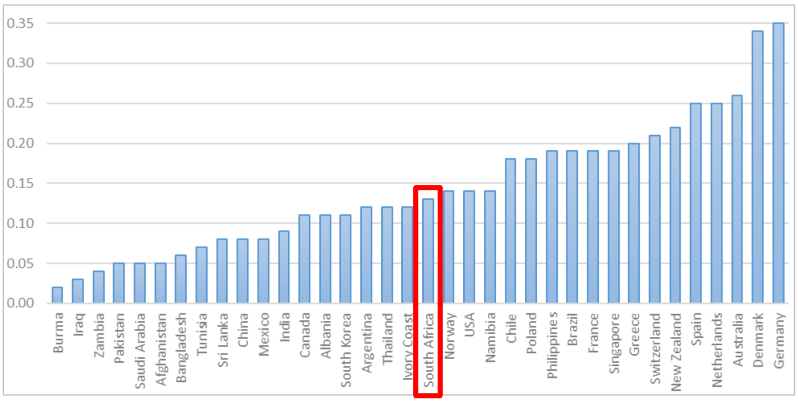


Figure 5: Aggregated electricity tariffs in USD per kWh (Y-axis) for selected countries (Bradshaw and Martino, 2019)

Figure 6 provides a visualization of residential electricity tariffs in South Africa, showing the average monthly electricity consumption on the X-axis. The average of these electricity tariffs is shown with a bolder line and the aggregate electricity tariff according to (GlobalPetrolPrices.com, 2019) with a dark brown line. The data for the individual distributors was collected from the websites of the distributors (City of Cape Town, 2019; City of Ekurhuleni, 2019; City of Tshwane, 2019; Eskom, 2019; eThekwini Municipality, 2019; Gildenhuys, 2019; NMBM, 2019; Stellenbosch Municipality, 2019).

The contrast between the declining block tariff for residential customers in South Africa, as is evident in Figure 6, and the inclining block tariff (typically including set charges) that German households are charged with, is illustrated in Figure 7.

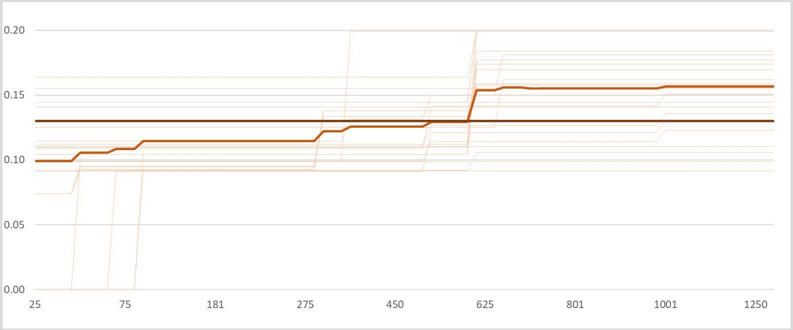


Figure 6: Residential electricity tariffs in South Africa, for representative municipalities (thin brown lines), the average of these individual residential electricity tariffs (bold, light brown) and the aggregate for all electricity tariffs for South Africa from (GlobalPetrolPrices.com, 2019) (dark brown). The X-axis shows the kWh used per month. The Y-axis is the cost per kWh converted to USD (0.0715 ZAR : 1 USD)

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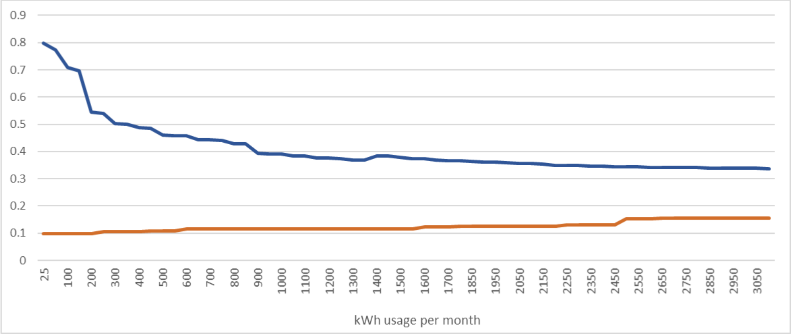

Figure 7: Average of individual residential electricity tariffs for South Africa (brown, from Figure 6) compared to average of individual residential electricity tariffs for Germany (blue)

SSEG tariffs: When rooftop PV is installed on an electricity customer's property, and depending on the specific regulation and the electricity utility involved, the electricity customer either stays on the same tariff structure as before the installation, or the electricity tariff is changed to a new tariff structure. New electricity tariffs that allow for the rooftop PV installation are referred to as *small-scale-embedded-generation* (SSEG) tariffs, which can be based on *net-metering,* where the electricity consumed and the electricity fed back into the grid are charged at the same rate. This could mean that a rooftop PV installation can generate electricity all day and feed this into the grid whilst allowing the prosumer to use grid electricity at the same cost in the evening. Net metering tariffs can also be more sophisticated and charge at a TOU rate, which could mean that the electricity fed back into the grid is paid for at a different rate than the electricity used, depending on the time of the day (or the time of year).

In areas where the installations of rooftop PV is actively encouraged and financially incentivized, the tariff paid to the prosumer for electricity fed back into the grid could be the same rate (net metering) or at a higher rate (when the installations are actively encouraged) than the electricity bought by the prosumer from the utility. More often though, the excess electricity fed into the grid is paid for at a lower rate than what customers typically pays for electricity consumed from the grid. This differentiation in the tariff is to compensate the utility for the costs it still incurs to supply the customer with electricity.

Electricity has the unique characteristic that it needs to be consumed at the moment it is generated. It is for this reason that, electricity generated at different times of the day, week or year, and for different applications, is generated at different costs and is bought at different rates. As illustration, one might be perfectly willing to switch off your lights at night, or do washing at a different time of the day, but less willing to switch of an air conditioner at midday or the stove while preparing an evening meal. Research has in fact shown that residential electricity consumption behavior does not shift easily. This might be due to the historically low cost of electricity, the inelasticity of electricity pricing, a delayed effect not yet measured or as yet unknown factors (EU-INOGATE Programme, no date; de Lange, 2008; Salvoldi, 2008, no date; Mendonca, Jacobs and Sovacool, 2010; Sorasalmi, 2012; Kelly, 2015; Hobman *et al.*, 2016; Presutti, Bruce and Macgill, 2017)

The immediacy of electricity means that electricity customer classes that use electricity in the day time when the sun is shining and do not close on weekend or public holidays are best suited for rooftop PV installation, as all of the electricity generated could be self-consumed. Businesses or households that do not have continuous day time electricity use will need to ensure that electricity can be fed into the grid and would probably want to be compensated for this. Residential electricity customers typically do not self-consume a high percentage of rooftop PV electricity generated due to their dis-aggregated electricity usage patterns. Note that electricity generated during a power cut is curtailed if not used on site and the income forgone.

Furthermore, if the tariff regime for residential customers (with or without rooftop PV) is changed from a simple energy-based tariff (that might also include set charges) to a more complex tariff (TOU, peak demand charges etc.), the cost of the new, more sophisticated, meters as well as the cost of the new, more sophisticated, billing regime should be weighed up against the implications of the desired outcome.

Although the installation of rooftop PV is generally not actively encouraged in South Africa, installation guidelines and SSEG tariffs are available in most major cities as well in some smaller towns. While C&I electricity customers can benefit from an accelerated depreciation for tax purposes (100% deducted as an expense in year 1), residential electricity customers do not qualify for this incentive. Electricity customers with rooftop PV are typically expected to apply at their distribution company, to install bi-directional meters (unless no electricity will be fed back into the grid) and to pay for these meters. These SSEG tariffs usually consist of a time-based component and active energy charges. The electricity fed back into the grid is normally refunded at the same level as what the distributer purchases electricity from in that time slot, which is typically a lower charge than the electricity consumed. In some cases, the SSEG tariff is a TOU tariff (Janisch, Euston-Brown and Borchers, 2012; Korsten *et al.*, 2017; Scholtz *et al.*, 2017; City of Cape Town, 2019; City of Ekurhuleni, 2019; City of Tshwane, 2019; Eskom, 2019; eThekwini Municipality, 2019; NMBM, 2019; Stellenbosch Municipality, 2019).

5. Modeling methodology

There are multiple methods with which to model the electricity system to assist policymakers with decision making, including those traditionally used in electrical engineering. However, it is becoming necessary to amplify these with new design tools, such as the proposed agent based software and system dynamics modeling techniques that are able to capture the complex system behavior and observe the emergent behavior of the system (Kremers *et al.*, 2010). Most of the existing models only include the influence that electricity tariffs and connection costs might have on rooftop PV adoption and do not model the impact that this same rooftop PV adoption has on electricity tariffs or on interconnection costs (Coley *et al.*, 2018b).

This decision-making tool uses a combination of system dynamic-, agent-based- and discreet event modeling. These three modeling techniques are described below;

System dynamic modeling has been in use for about seventy years. It is "the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" (Forrester, 1961). Processes are represented as stocks, flows between stocks and information determining the values of these flows (Borshchev and Filippov, 2004).

With **agent based modeling**, the "selfish" behavior of "agents" are defined by the modeler at an individual level, with the overall system behavior emerging as a result of the decisions made by these individual agents, based on the environment they find themselves in (Borshchev and Filippov, 2004).

Discrete event modeling was developed in 1961as a discrete time simulation general-purpose programming language for IBM (Gordon, 1961). With this type of modeling, entities are passive objects that travel through blocks in a flowchart in a typical algorithmic way (Borshchev and Filippov, 2004).

6. The model

The tool does not aim to arrive at a definitive answer, but rather to investigate and build a better understanding of the complex interactive nature of "agent" actions over time to investigate whether it is possible for a stable and more prosperous system to emerge from these independent or "selfish" decisions. "Prosperity" in this sense refers to the financial viability on all the levels individually and together, but also includes a healthier and more robust environment as well as fair and equitable in social terms. The tool also allows decision makers to rank their goals according to their own priorities in order to observe how the scenarios are influenced by this. The input of pre-determined cut-off points (greenhouse gas (GHG) emissions, cost, stability etc.) is also possible.

The measurement criteria with which to evaluate the outputs of modeling runs using the tool include; the impact that the policy environment has on the rate of PV installations over time and; how the electricity tariffs evolve or; how a pre-determined tariff trajectory will influence the system in other ways. In addition, measurement criteria also include;

- **Financial implications,** including the business case for each entity;
- **System stability**, including the likelihood of excessive ramp rates at system level and the likelihood of system overload at local level;
- **Environmental impact,** focusing on the level of GHG emissions

The entities or "agents" in the tool are; the electricity end consumers; clusters of electricity end consumers located in close proximity to each other; distribution utilities; transmission utilities; generators and; policy agents. Some of these agents are embedded within each other. All of these agents make their own decisions independently from each other, but are influenced by the decisions of other agents that they observe. Agents do not have perfect knowledge of the entire system, but are only affected by the part of the system that they are able to observe. However, even in the case where agents have perfect knowledge, it does not necessarily follow that their actions and decisions are rational.

The agents are described below. For more information on these agents, see Table 1.

Level 1 agents, electricity end-consumers: These entities include; households, businesses, factories, warehouses, farms, schools, government buildings. These agents purchase electricity from Level 2, Level 3 or Level 6 agents. In addition to its type, each agent is also assigned certain attributes including; location; property size; building size and; property value. According to their geographic location, these agents either purchase electricity directly from a utility (Eskom or the metro/municipality) or via their clustered neighborhood or estate, who in return purchase electricity directly from a utility. The starting state of these entities is either *"with a rooftop PV system installed"* or *without.* The decisions of these agents as to whether to install a rooftop PV or not are based on their own attributes (available space, solar resource, financial attributes, electricity use) as well as on the attributes of their geographic location (who they purchase electricity from, at what tariff, how many rooftop PV installers operate in their area and what the installation price is, who they are in contact with). These agents make decisions at two-month intervals and their decisions are implemented within one month of a decision.

Level 2 agents, "neighborhoods" or "estates": These entities are made up of clusters of Level 1 Agents (residential, commercial, industrial or mixed-use) and purchase electricity either from Level 3 agents or directly from Level 5 agents, which is then sold on to the Level 1 agents in their cluster. They can make decision on the regulation or promotion of installations of rooftop PV by their residents and their decisions are influenced by the actions of their residents (while the residents' decisions in turn are affected by these rules). These entities can also decide to install rooftop PV on communal buildings or on open ground and have the ability to change the structure of the tariff that they charge their residents. They will make decisions every six months and their decisions will take three months to implementation.

Level 3 agents, distribution utilities: These include municipal electricity distributors and the distribution arm of Eskom. These entities have independent decision making capabilities, however, their decisions are based on the decisions of the entities within their distribution area. Distributors purchase electricity from Level 4 and Level 5 agents, and sell to Level 1 and Level 2 agents. Level 3 agents have the ability to influence or promote the installation of rooftop PV to their customers and also have the ability to install rooftop PV on their own buildings or on open land. They will make decisions once a year and their decisions will take six months to be implemented.

Level 4 agents: Transmission utility: This entity sells electricity to Level 3 agents and can influence their decision-making. This entity has the ability to change the structure of the tariff that it charges its customers based on approval from the regulator. They will make decisions once a year and their decisions will take six months to be implemented.

Level 5 agents: Generation utility: This entity is a standalone generator with no significant own electricity use and no mandate for transmission and distribution. Generation units that are owned by level 1 – 4 agents where the electricity generated is used on site, are integrated into the attributes of that agent. Level 5 agents are able to sell electricity to Level 1, Level 2, Level 3 and Level 4 agents.

Level 6 agents: Policymakers: These are regional and national government departments and agencies as well as regulators, such as the National Energy Regulator of South Africa (NERSA). These agents make policy decisions that affect the behavior of all the other agents. However, the decisions that these policy agents make are also based on the decisions of the other agents at that time. Policy decisions that are made on level 1-5 agent level are integrated in the attributes of the agent.

Additional information on the agents, their attributes and determinants are provided in Table 1.

Table 1: Model for the policy tool illustrating the different agents, interactions and attributes

	Embedded in	Embeds	Type	Attributes	Determinant of attribute
Level 1 agents: Electricity end-consumers	Level 2 / Level 3 / Level 6	n/a	Households	Geographic location	Distributor (and tariff) / Neigborhood effect / Solar resource / cost of PV / PV installers in area
				Property value	Property value / property size determinant of likelihood to install PV
				Property size	Property value / property size determinant of likelihood to install PV Space availability
				Property type	Suitabilty for PV
				Owner occupied / rental	Likelihood to install PV
				Trust in utility	Likelihood to install PV
				Has PV / No PV	Starting attribute, re-evaluated every 2 months.
			Commercial	Geographic location	Distributor (and tariff) / Neigborhood effect / Solar resource / cost of PV / PV installers in area
				Property size	Suitabilty for PV
				Property type / occupancy	Suitabilty for PV
				Trust in utility	Likelihood to install PV
				Has PV / No PV	Starting attribute, re-evaluated every 2 months.
				Connction type (LV/MV)	Likelihood to install PV
			Industrial	Geographic location	Distributor (and tariff) / Neigborhood effect / Solar resource / cost of PV / PV installers in area
				Property size	Suitabilty for PV
				Property type / occupancy	Suitabilty for PV
				Trust in utility	Likelihood to install PV
				Has PV / No PV	Starting attribute, re-evaluated every 2 months.
				Connction type (own line, shared connection)	Likelihood to install PV
			Government	Geographic location	Distributor (and tariff) / Neigborhood effect / Solar resource / cost of PV / PV installers in area
				Property size	Suitabilty for PV
				Property type / occupancy	Suitabilty for PV
				Has PV / No PV	Starting attribute, re-evaluated every 2 months.
				Connction type (own line, shared connection)	Likelihood to install PV
Level 2 agents: Clusters of Electricity end-consumers	Level 3, Level 5, Level 6	Level 1	From Level 1 attributes	From Level 1 attributes	From of Level 1 determinants
					Distributor
					Generator
					Policy
Level 3 agents: Distribution utilities	Level 4	Level 1, Level 2	National Utility / Metro / small municipality	From Level 1 and 2 attributes	From Level 1 and Level 2 determinants
					Distributor
					Generator
					Policy
				Financial position	
				Own policies	Starting attribute, re-evaluated every 1 year
				Tariff regime	Starting attribute, re-evaluated every 1 year, new regime in effect after 6 months
				System strenght	Likelihood of power failures
				Own generation	Starting attribute, re-evaluated every 1 year
Level 4 agents: Transmission utility	n/a	Level 3	Eskom	From level 1, 2, 3 attributes	
				System strenght	Likelihood of power failures
				Policy implementation	Policy
Level 5 agents: Generation utility	n/a	n/a	Wind, PV, CSP, Coal, Nuclear, Wind, Hydro, Pumped hydro, Energy storage	Location	Resource, generation forecast
				Technology	Generation forecast
				Age	Generation forecast / retirement / new generation
				Financial position	Retirement / new generation
				Historical performance	Generation forecast
Level 6 agents: Policy environment	n/a	Level 1, Level 2, Level 3, Level 4, Level 5	National: (DoE, DST, dti, NERSA), regional (provincial) and local (municipal)	Targets, programmes, commitments, resource plans, rules and regulations, incentive structures, tariff policies, tax benefits, rebates, subsidies	Likelihood to install PV

7. Preliminary results and conclusions

Utilities find themselves in an unenviable position. While they are aware of, and in support of, the need to move the power system away from fossil fuel generation and although they recognize the role of rooftop PV to drive this transition, increased penetration will impact on their revenue. The increase of electricity prosumers, acting as disruptors to a previously linear electricity system, is making it increasingly difficult for utilities to respond optimally. In this context, “optimally” means ensuring a stable overall electricity system (from the local to the national) that is operationally and financially viable, while responsive to the need to reduce the dependence on fossil fuel generated electricity. In a South African context, the challenge is compounded by low levels of reporting of rooftop PV installations.

The tool described in this paper is under development. Preliminary results using a representative dataset are promising. The tool is able to illustrate the impact that agent decisions have, both individually as well as collectively, and also how agent decisions change over time in accordance with a changing system. In addition it is also to illustrate how individual choices of different agents are both influenced by the state of the system and influence the state of the system in turn.

Essentially, the tool is a first stab at surfacing the complexity of the electricity system to decision makers, demonstrating the qualities of the system and making explicit the foundational change from a system controlled by a single agent to numerous agents. The development follows an iterative process a key next step is to demonstrate the tool to selected utilities with the purpose of refining it further as well as to provide an opportunity for policy makers to develop an understanding of the properties of the tool and how it can add value.

Given the interactions between the different variables and emergent properties of the system, the aim of the tool is not to deliver definitive answers to decision makers, but rather to enable them to develop a better understanding of the dynamics of a system that consists of many independent decision makers, including the policymakers themselves. It is posited here that making the complexity of the system evident enables decision makers to act in a way that will be to the benefit of the whole system, especially with regards to the observation of the emergent properties and the interaction between events that are within the utilities’ control and the ever changing decisions of their customers.

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