UTILITY PRICING DEATH SPIRAL

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Abstract

Due to the increasing costs of an erratic supply of electricity that is provided by utility companies, many customers may resort to using renewable energy. As a result of losing customers, tariff prices for the remaining customers will need to increase in order to cover the grid and infrastructure maintenance costs. This creates further incentive to use renewable energy sources. In this paper we develop a mathematical model that describes the effect of customers supplementing their electricity needs with renewable energy sources on the tariff prices. The conditions leading to a utility death spiral are derived. Several strategies are discussed with the purpose of avoiding the occurrence of a death spiral.

1 Introduction

Utility companies (such as municipalities) generate and supply electricity to customers for both commercial and household usage. In recent years, concerns have been raised about the possibility of a “utility death spiral”, which could result in dramatic increases in the price of electricity and the closure of many affected utilities. If utility companies do not change their present strategy of the pricing and the

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method of production of electricity, they will not be able to compete with companies such as renewable energy manufacturers, and their relevance in the future will be uncertain [5, 6, 7, 8]. In this work we investigate the conditions under which a utility death spiral is likely to occur.

Utilities generate most of their revenue through electricity tariffs and their income is dependent on a consistent demand for electricity. However, as the cost of renewable energy technology such as solar panels drops, many customers may begin to generate their own energy. This transition to renewable energy sources decreases the overall electricity demand from the utility and lowers their total revenue.

Costs for the maintenance and repair of infrastructure form a large part of the utility’s budget and need to be covered regardless of the drop in demand for electricity. In order to maintain their budget, tariff prices are increased. This creates further incentive for customers still connected to the grid to transition to renewable sources. A feedback loop is created as more and more users are tempted into using renewable energy and the utility must rely on a smaller pool of users to cover its costs.

In South Africa, utilities are even more sensitive to this problem because they provide cheap or free electricity to consumers that otherwise cannot afford to pay for it. Around 40% of all households are subsidized with free electricity through tariff structures imposed on the high and middle income households, businesses and industries [1]. The utility market is very fragmented with around 120 municipalities serving less than 1000 customers and around 90 municipalities receiving less than R1 million in revenue [1]. Further information can be found in [2, 3, 4].

The utilities are heavily dependent on high tariff customers, not only to subsidize the provision of free basic electricity but also to cover the cost of maintaining and expanding the national energy grid. Unfortunately, the high tariff customers are most likely to have the means and motivation to switch to some form of alternative energy.

The purpose of this research is to provide a mathematical model that explains the number of users in the different tariff groups and predicts the effects of possible strategies to maintain the utility’s income. Factors such as inconsistent electricity supply and high tariff prices will be taken into account in order to model the movement of users from high tariff groups to a group that supplements its electricity with renewable energy. Other relevant factors, such as the rate of economic growth, will be taken into account and discussed.

An outline of this paper is as follows: in Section 2 we develop a general mathematical model where the users are grouped into \( n \) tariff groups. In Section 3 we discuss the different strategies that can be implemented by the utilities in order to ensure their survival. A specific example is given in Section 4 and conclusions are provided in Section 5.
2 Mathematical Model

In this section we develop a mathematical model that describes the movement of customers between different tariff groups. The model incorporates several important factors which influence the size of each group. Economic growth results in a general movement of customers from lower to higher tariff groups as their demand for electricity increases. Users in the higher tariff groups are more likely to become dissatisfied with the high price of an inconsistent supply of electricity and may resort to using alternative energy sources. Users may also be forced to either reduce their usage or switch to alternative energy sources if the utility is unable to supply adequate energy to meet the overall demand.

2.1 General Model

We consider a general model in which the utility’s customers are divided into $n$ different tariff groups. We define the following variables:

- $G_i$ is the number of customers in tariff group $i$.
- $G_{n+1}$ is the number of potential customers who do not have access to the grid.
- $A$ is the number of customers who supplement their energy with alternative sources.
- $U_i$ is the average energy usage per customer for the $i^{th}$ group, where $i \in \{1, ..., n, A\}$.
- $T_i$ is the electricity tariff per unit of electricity of group $G_i$.
  Here, $T_n < T_{n-1} < \cdots < T_1$.
- $T_A$ is the electricity tariff for group $A$.
- $C_i$ is the production cost for the $i^{th}$ group per unit of electricity.
- $H_i$ is the fixed grid connection fee per customer for the $i^{th}$ group $G_i$.
- $H_A$ is the fixed grid connection fee per customer for group $A$.
- $G_{mi}$ is the number of customers in group $i$ that cannot switch to alternative energy sources. We have $G_i \geq G_{mi}$ for $i = 1, 2, ... n$.

2.2 Population Dynamics

The number of customers in each tariff group changes due to different factors that will be discussed in detail. The number of customers in each group at time $t$ is determined by the solutions to the equations:

$$\frac{dA}{dt} = \sum_{i=1}^{n} \left(\chi_i(t) + m_i(G_i - G_{mi})A\right) + r_1(G_1 - G_{m1})K(t)g(t),$$
\frac{dG_1}{dt} = \beta_2 G_2 - \chi_1(t) - r_1(G_1 - G_{m1})K(t)g(t) - m_1(G_1 - G_{m1})A,
\frac{dG_i}{dt} = \beta_{i+1} G_{i+1} - \beta_i G_i - \chi_i(t) - m_i(G_i - G_{mi})A - \, \, \, i = 2, 3, \ldots n,
\frac{dG_{n+1}}{dt} = -\beta_{n+1} G_{n+1} + r_n(G_n - G_{mn})K(t)g(t), \quad \text{(2.1)}
where \delta_{i2} is defined as
\delta_{i2} = \begin{cases} 1, & i = 2, \\ 0, & \text{otherwise.} \end{cases}

In the following subsections we explain the purpose of each term in detail.

2.2.1 Economic growth: \(\beta_i\)

The positive coefficients \(\beta_i\) relate to economic growth and specify the time rate at which customers are increasing their electricity usage and moving to higher tariff groups. Alternatively, we can define the coefficients \(\beta_i\) to be negative and thus model the situation of economic recession. Economic growth is beneficial to the utilities. As customers use more electricity, they pay higher tariffs providing the utilities with a higher income. The importance of economic growth will be illustrated in Section 4.

2.2.2 Interaction terms

The terms \(m_i(G_i - G_{mi})A\) describe the rate at which customers switch to alternative energy sources as a result of increasing awareness and popularity. We omit any interactions between customers in group \(A\) and those that are not able to switch to alternative energy sources, \(G_{mi}\).

2.2.3 Supply shortage

The terms \(r_i(G_i - G_{mi})K(t)\) represent the rate at which customers in a specific tariff group increase or decrease due to the available supply of electricity. We have
\[ K(t) = \frac{\sum_{i=1}^{n} (G_i U_i + \alpha_i A U_A)}{k(t)} - 1. \quad \text{(2.2)} \]

The parameter \(\alpha_i, 0 \leq \alpha_i < 1\) describes the percentage of energy \(U_A\) that is obtained from the grid by users in group \(A\). The remaining energy \((1 - \alpha_i) U_A\) is generated from renewable energy sources.

If \(K(t) > 0\) and the demand for electricity is greater than the supply \(k(t)\), then the terms \(-r_i(G_i - G_{mi})K(t)\) are negative resulting in a decrease in the number of customers in that group. If \(K(t) < 0\) then the demand for electricity is less than the supply \(k(t)\) and the terms \(-r_i(G_i - G_{mi})K(t)\) are now positive which
indicates an increase in the number of customers in that group. Loosely defined, the \( r_i \) coefficients represent the possibility of a customer moving to a different tariff group (or alternative energy) when the utility is failing to keep up with the current demand for energy.

If \( K(t) > 0 \) then some customers in group \( G_1 \) will simply start to generate their own electricity and therefore move to group \( A \). However, customers in the lower tariff groups may be unable to switch to renewable energy sources as the initial costs are very high. Therefore, these customers will have to reduce their energy consumption and move to the tariff group immediately below. Customers in the lowest tariff group may move to group \( G_{n+1} \) and be left without electricity. The terms \( r_{i-1}(G_{i-1} - G_{m(i-1)})K(t)g(t) \) describe this scenario, where

\[
g(t) = \begin{cases} 
1, & K(t) > 0, \\
0, & \text{Otherwise.}
\end{cases} \tag{2.3}
\]

### 2.2.4 Tariff increases and alternative energy costs

The \( \chi_i(t) \) term describes the rate at which customers switch to alternative energy due to tariff increases and decreasing renewable energy costs:

\[
\chi_i(t) = \frac{G_i - G_{mi}}{q} \sigma \left(1 - \frac{a_i(t)}{T_i} - \gamma\right), \tag{2.4}
\]

where

\[
\sigma(z) = \frac{1}{1 + e^{-z}}, \tag{2.5}
\]

\[
a_i(t) = \frac{S(t)}{U_A} + \alpha_i T_i. \tag{2.6}
\]

Here, \( 1/q \) is the proportionality constant. The term \( a_i(t) \) describes the unit costs associated with buying and maintaining renewable energy sources and obtaining a portion \( \alpha_i \) of energy from the grid. Calculating an appropriate expression for \( a_i(t) \) poses a challenge, because the significant costs of alternative energy \( S(t) \) are generally once-off expenses (for renewable solar energy, for example) related to purchasing and installing the necessary equipment. By contrast, the utility charges customers a tariff per unit of electricity. In order to compare the two, we consider an equivalent cost per unit of electricity by dividing the current initial costs of alternative energy \( S(t) \) (equipment and installation) by the amount of energy \( U_A \) that will be generated over the lifetime \( (p) \) of the equipment. Based on the assumption that the customer will remain connected to the grid and continue to draw a portion of their energy from the utility, this tariff is then weighted proportionally with the utility tariff:

\[
a_i(t) = (1 - \alpha_i) \frac{S(t)}{(1 - \alpha_i)pU_A} + \alpha_i T_i,
\]

which after simplifying gives (2.6).
The function $S(t)$ is given by

$$S(t) = S_0 \exp[-\rho t] + S_m,$$  

where $S_m$ is the lowest cost possible to use renewable energy sources. We see that as $t \to \infty$, $S(t) \to S_m$. The parameter $\rho$ defines the exponential rate at which the costs decrease with time. At $t = 0$, $S(t)$ is at its maximum value of $S_0 + S_m$. As technology improves it is likely that the costs of generating electricity will decrease. Higher tariff prices will also persuade customers to use renewable energy sources.

The parameter $\gamma$ describes the effect of other factors that might influence the decision to switch to alternative energy. For example, if alternative energy is slightly more expensive, $T_i(t) < a_i(t)$, customers may still be tempted generate their own electricity due to increased awareness of the preservation of the environment and $\gamma$ would be negative. On the other hand, if the high initial costs of alternative energy are a barrier, then customers would be less likely to switch even when $T_i(t) > a_i(t)$, and $\gamma$ would be positive.

### 2.3 Death spiral conditions

The utility death spiral occurs when the rate of economic growth $\beta_i$ is too low to compensate for the effects of higher tariffs and the unreliable supply of electricity.

As more customers start to generate their own electricity, tariff prices will need to increase in order to cover the costs of maintaining and expanding the grid. If tariff prices are too high, less customers will be inclined to use the electricity provided by the utilities. This would be detrimental to customers that cannot afford electricity in situations where they are subsidized by the paying customers in the higher tariff groups. In each group $G_i$, $i = 1, 2, ..., n$, the terms $\beta_i G_i$ result in a positive increase in that tariff group. Economic growth enables more customers to have a greater electricity usage and as a result the tariffs will not increase drastically.

### 3 Strategies

Energy utilities are responsible for supplying affordable and reliable electricity to as many customers as possible. This includes discriminatory pricing practices that allow the utilities to subsidise the poor. There are numerous strategies that the utilities could implement. In general these strategies should allow the utilities to generate sufficient revenue to maintain their infrastructure and cover the variable costs of energy production.

The utility’s revenue is generated by charging tariffs $T_i$ on the average energy usage per customer $U_i$. In addition, a fixed monthly fee $H_i$ is sometimes charged for access to the grid. The money obtained from tariffs and grid access assist in covering the variable costs of energy production $C_i$ and infrastructure $F(t)$. The energy production costs are influenced by the location of the consumer in relation to the production facility. Consumers of alternative energy generally still rely on
the utility’s energy in order to meet their demands. The proportion of their energy generated by the utility is denoted by $\alpha_i$.

Using the expressions defined above, we can express the utility’s profit in terms of revenue and expenses:

$$\text{Profit} = \varepsilon + \sum_{i=1}^{n} (G_i (U_i T_i + H_i) + \alpha_i AT_A U_A) + AH_A - \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i AC_A U_A \right].$$

(3.1)

In equation (3.1), $\varepsilon$ denotes any funding from external sources.

By setting the profit equation equal to 0, we can determine the tariffs $T_i$, grid access fees $H_i$ and external sources of funds $\varepsilon$ that are required to cover the utilities’ costs.

### 3.1 External funding

Utilities that do not or cannot change tariffs and grid access costs must rely solely on external funding in order to cover their costs:

$$\varepsilon = - \left[ \sum_{i=1}^{n} G_i (U_i T_i + H_i) + \alpha_i AT_A U_A + AH_A \right] + \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i AC_A U_A \right].$$

(3.2)

Shortfalls are subsidised by external sources and surpluses return to these external sources. This strategy would be suitable for a subsidiary to a chain of utilities. The chain can distribute profits across its subsidiaries thus ensuring that subsidiaries with little revenue can continue to supply electricity. This strategy could also be applied in cases where the utility is a national asset and can be subsidised by tax revenue.

The next strategies consider the situation where external funding cannot be relied upon in order to cover the shortfall.

### 3.2 Tariff increase

Utilities might choose to subsidise low-income consumers with tariffs charged to high-income consumers:

$$T_1 = \frac{-\varepsilon - \sum_{i=2}^{n} G_i (U_i T_i) - \sum_{i=1}^{n} G_i H_i - \alpha_i AT_A U_A - AH_A + \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i AC_A U_A \right]}{U_1 G_1}.$$  

(3.3)

This strategy allows any shortfall in revenue to be offset by the tariff of the highest income group $G_1$. If the revenue from the other tariff groups and the external funding is more than sufficient to cover total expenses then this tariff could become
negative. It is assumed that this model is not applied under such circumstances. In other words, this strategy is only valid for $T_1 > 0$. The tariff is dependent on the usage and size of the highest income group, or equivalently, its total usage. If this group’s total usage becomes sufficiently low due to customers switching to renewable energy sources, then the tariff fee could become very high. If the tariff becomes unaffordable the death spiral could ensue. For the above reasons this strategy should be viewed with caution.

### 3.3 Grid fee increase

Utilities might choose to subsidise low income consumers with a grid access fee charged to high income consumers:

$$H_1 = \frac{-\varepsilon - \sum_{i=1}^{n} G_i (U_i T_i) - \sum_{i=2}^{n} G_i H_i - \alpha_i AT_A U_A - AH_A + \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i ACA U_A \right]}{G_1}. \tag{3.4}$$

As discussed above, it would be inappropriate for the grid access fee to become negative, and thus this strategy applies when $H_1 > 0$. This strategy is dependent on the size of the high tariff group. This makes it more reliable since it depends on the number of customers $G_1$ and not the total usage $U_1 G_1$. This strategy does not alleviate the threat of the death spiral. If group $G_1$ becomes very small the grid access cost may be unaffordable and customers in that group are more likely to switch to renewable energy sources decreasing the group’s number further.

### 3.4 Distributed tariff increase

Instead of relying on a single tariff group to cover the shortfall in the utility’s revenue, it may be fairer to distribute these costs across some or all of the different tariff groups. If we take $Y$ to be the total shortfall, i.e

$$Y = -\varepsilon - \sum_{i=1}^{n} G_i (U_i T_i + H_i) - \alpha_i AU_A T_A - AH_A + \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i ACA U_A \right], \tag{3.5}$$

then each group’s tariff will increase by $\mu_i Y$ such that

$$\sum_{i=1}^{n} G_i U_i \mu_i + \alpha_i AU_A \mu_A = 1, \tag{3.6}$$

where $\mu_i$ can be varied to determine how much the tariff for each group will change. This strategy allows the utility to redistribute the shortfall in a fair and practical manner. If the parameters $\mu_i$, $i = 1, 2, \ldots, n$, $A$ are chosen such that equation (3.6) is satisfied then

$$0 = \varepsilon + \sum_{i=1}^{n} G_i U_i (T_i + \mu_i Y) + \sum_{i=1}^{n} G_i H_i + \alpha_i AU_A (T_A + \mu_A Y) + AH_A$$
\[- \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i A C A U_A \right]. \tag{3.7}\]

The coefficients \( \mu_i \) allow the utility to adjust the burden on any tariff group such that the marginal cost of acquiring energy \( T_i + \mu_i Y \) is not too high. Shortfalls do not have to exclusively be levied against the small high tariff groups, since even relatively small increases in the tariffs of large, low tariff groups would make a significant contribution to \( Y \). This is a step towards alleviating the death spiral.

### 3.5 Distributed grid fee increase

Using similar arguments to those expressed in Section 3.4, the utility could distribute its costs via grid fees instead of tariffs. In this case, the grid fee for each group would increase by \( \omega_i Y \), such that

\[
\sum_{i=1}^{n} G_i \omega_i + A \omega_A = 1. \tag{3.8}\]

Thus we obtain

\[
0 = \varepsilon + \sum_{i=1}^{n} G_i U_i T_i + \sum_{i=1}^{n} G_i (H_i + \omega_i Y) + \alpha_i A T_A U_A + A (H_A + \omega_A Y) \]

\[- \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i A C A U_A \right]. \tag{3.9}\]

In this case, a customer’s usage does not contribute directly to \( Y \) and so it might be necessary to assign much lower weights to low-income, low-usage groups. An advantage of this strategy is that the \( \omega_A \) coefficient can be manipulated to avoid creating any additional incentive to move to alternative energy. This strategy can also help utilities to ensure that customers continue to contribute to the maintenance of the grid infrastructure even if they choose to reduce their electricity usage.

### 3.6 Distributed tariff and grid fee increase

A combination of the above strategies allows the utility to change both the electricity tariffs and grid fees by amounts \( \mu_i Y \) and \( \omega_i Y \) respectively, where

\[
\sum_{i=1}^{n} G_i U_i \mu_i + \alpha_i A U_A \mu_A + \sum_{i=1}^{n} G_i \omega_i + A \omega_A = 1. \tag{3.10}\]

In order for the utility to cover its costs we have

\[
0 = \varepsilon + \sum_{i=1}^{n} G_i (U_i (T_i + \mu_i Y) + H_i + \omega_i Y) + \alpha_i A U_A (T_A + \mu_A Y) + A (H_A + \omega_A Y) \]
 Utility pricing death spiral

\[- \left[ F(t) + \sum_{i=1}^{n} (G_i U_i C_i) + \alpha_i AC_A U_A \right]. \] (3.11)

This strategy is the most flexible, as it allows the utility to distribute any shortfalls over all tariff groups and decreases the risks associated with very high tariffs or grid fees. The utility may choose to reduce the pressure on a specific group or to increase the contribution of another group in order to compensate for changing economic conditions and other important factors.

4 Example

In this section, we use a simple example to illustrate the model discussed in previous sections. We consider three different tariff groups: high, medium and low with population numbers \(G_1, G_2\) and \(G_3\) respectively. The group with population \(A\) denotes customers who use alternative energy to supplement their usage and group \(G_4\) represents those that do not have access to the energy grid. Figure 1 illustrates the different groups as well as the parameters which indicate the movement of customers between groups. We first develop the model and then discuss different strategies that can be implemented in order to prevent the utilities from collapsing.

Figure 1: Tariff group dynamics.

The following assumptions are made:

- Customers using alternative energy remain connected to the grid and draw a portion \((\alpha)\) of their monthly energy usage from the utility.

- Once a customer has invested in an alternative energy source, they are unlikely to stop using it in favour of the utility.

- When the electricity demand exceeds the utility’s capacity, high tariff customers respond by moving to alternative energy sources.
• High tariff customers are also more likely to move to alternative energy if it is cheaper than the utility’s energy, or if they are exposed to many other alternative energy users.

• The tariff of the high income customers $T_1$ is equal to the tariff charged to customers using alternative energy sources $T_A$.

• The medium and low tariff customers respond to load shedding by reducing their energy consumption, which may result in them moving to a low tariff/no energy group.

• Economic growth causes customers to increase their energy consumption and move to a higher tariff group.

• The low tariff group receives subsidised energy at below-cost rates.

• The infrastructure costs, $F(t)$, increase linearly according to the total number of customers on the grid.

### 4.1 Governing Equations

The population dynamics illustrated in Figure 1 are governed by the following equations:

$$\frac{dA}{dt} = \chi(t) + r_1(G_1 - G_m)K(t)g(t) + m(G_1 - G_m)A,$$

$$\frac{dG_1}{dt} = \beta_2G_2 - \chi(t) - r_1(G_1 - G_m)K(t)g(t) - m(G_1 - G_m)A,$$

$$\frac{dG_2}{dt} = -\beta_2G_2 + \beta_3G_3 - r_2G_2K(t)g(t),$$

$$\frac{dG_3}{dt} = \beta_4G_4 - \beta_3G_3 - r_3G_3K(t)g(t) + r_2G_2K(t)g(t),$$

$$\frac{dG_4}{dt} = -\beta_4G_4 + r_3G_3K(t)g(t) + r.$$  \quad (4.1)

The product $K(t)g(t)$ indicates whether there is an energy supply shortage, as well as the severity of the shortage. The equation for $K(t)$ is given by setting $n = 3$ in equation (2.2):

$$K(t) = \frac{\sum_{i=1}^{3} G_iU_i + \alpha AU_A}{k(t)} - 1,$$  \quad (4.2)

where $k(t)$ represents the utility’s total supply capacity. The function $g(t)$ is defined in equation (2.3).

The function $\chi(t)$ describes the probability of high-tariff users moving to alternative energy based on the comparative cost of alternative energy sources as defined in equations (2.4)-(2.7).
4.2 Strategies

We now give a brief description of the different strategies that can be applied to this simplified example in order to cover any shortfall in the utility’s costs.

4.2.1 External funding

The simplest way to ensure that the utility’s income remains stable is to use an external source of funding which covers any shortfall in revenue. For large-scale utilities, this funding is most likely to come from rates and taxes. The equation used to calculate the amount of external funding required for this example is found by setting $n = 3$ and $T_1 = T_A$ in equation (3.2):

$$
\varepsilon = \left[ F(t) + \sum_{i=1}^{3} (G_i U_i C_i + \alpha A C A) - \sum_{i=1}^{3} G_i (U_i T_i + H_i) + \alpha A U A T_1 + A H A \right].
$$

This strategy may be viable in the long term, provided that the revenue shortfall does not become too large to be offset by external funds.

For the next strategies we will assume that for this particular example the external funding $\varepsilon$ is zero.

4.2.2 Tariff increase

The utility may decide to use tariff increases to cover any shortfall in their revenue. There are a number of different ways to divide the shortfall amongst the different tariff groups. In a worst-case scenario, we assume that only the high tariff group and the alternative energy group are able to absorb these costs. In this case, the tariff is calculated as follows:

$$
T_1 = \frac{F(t) + \sum_{i=1}^{3} G_i U_i C_i + \alpha A U A C A - \sum_{i=2}^{3} G_i U_i T_i - \sum_{i=1}^{3} H_i G_i - H A A}{G_1 U_1 + \alpha A U A}.
$$

This tariff structure is very likely to cause a death spiral. It works well when the economy is strong and there are many customers moving into the high tariff group to replace those who leave, but this kind of growth is unlikely to continue indefinitely.

In the long-term, this strategy will only be successful if the cost of alternative energy remains high relative to the utility’s tariffs.

4.2.3 Grid fee increase

Another way for the utility to increase its income is to charge customers a higher grid connection fee. In this case, we assume that the high tariff and alternative energy group will be charged the same grid fee. This strategy is less likely to encourage customers to switch to alternative energy, as they would not be able to avoid the increasing grid fees by lowering their energy usage. The following equation is used to calculate the appropriate grid connection fee for these users:
This is probably a fairer way to ensure that the utility has enough money to cover its infrastructure costs as opposed to the strategy in Section 4.2.2. However, increases in the grid fees would probably still result in a great deal of unhappiness amongst the utility’s customers. As alternative energy becomes cheaper, there is also a danger that customers will invest in technology which allows them to leave the grid entirely and thus avoid paying these fees.

### 4.2.4 Distributed tariff increase

The distributed tariff increase strategy can also be applied. Each tariff increases by \( \mu_i Y \). We set \( n = 3 \) and \( T_1 = T_A \) in equation (3.5) in order to obtain the shortfall \( Y \):

\[
Y = -\sum_{i=1}^{3} G_i (U_i + T_i + H_i) - \alpha AU_A T_1 - AH_A + \left[ F(t) + \sum_{i=1}^{3} (G_i U_i C_i + \alpha AC_A U_A) \right].
\]  

(4.5)

In order to balance this shortfall we vary \( \mu_i \) and \( \mu_A \) such that

\[
\sum_{i=1}^{3} G_i U_i \mu_i + \alpha AU_A \mu_A = 1,
\]  

(4.6)

giving

\[
0 = -\sum_{i=1}^{3} G_i U_i (T_i + \mu_i Y) + \sum_{i=1}^{3} G_i H_i + \alpha AU_A (T_A + \mu_A Y) + AH_A
\]

\[
- \left[ F(t) + \sum_{i=1}^{3} (G_i U_i C_i + \alpha AC_A U_A) \right].
\]  

(4.7)

This strategy allows the utility to redistribute the shortfall in a fair and practical manner.

### 4.2.5 Distributed grid fee increase

The utility could distribute its costs via grid fees instead of tariffs. Each fee increases by the amount \( \omega_i Y \). In order to balance the shortfall, we vary \( \omega_i \) and \( \omega_A \) such that

\[
\sum_{i=1}^{3} G_i \omega_i + A \omega_A = 1,
\]  

(4.8)
giving
\[
0 = -\sum_{i=1}^{3} G_i U_i T_i + \sum_{i=1}^{3} G_i (H_i + \omega_i Y) + \alpha A T_A U_A + A (H_A + \omega_A Y)
\]
\[
- \left[ F(t) + \sum_{i=1}^{3} (G_i U_i C_i) + \alpha A C_A U_A \right],
\]
(4.9)

which will offset the shortfall \(Y\) given in equation (4.5).
A customer’s usage does not contribute directly to \(Y\). This strategy may designed
to deter people from switching to alternative energy sources.

4.2.6 Distributed tariff and grid fee increase

A combination of the strategies in Sections 4.2.4 and 4.2.5 is to change both the
electricity tariffs and grid fees by amounts \(\mu_i Y\) and \(\omega_i Y\) respectively. Satisfying the condition
\[
\sum_{i=1}^{3} G_i U_i \mu_i + \alpha A U_A \mu_A + \sum_{i=1}^{3} G_i \omega_i + A \omega_A = 1,
\]
(4.10)

leads to
\[
0 = \sum_{i=1}^{3} G_i (U_i (T_i + \mu_i Y) + H_i + \omega_i Y) + \alpha A U_A (T_A + \mu_A Y) + A (H_A + \omega_A Y)
\]
\[
- \left[ F(t) + \sum_{i=1}^{3} (G_i U_i C_i) + \alpha A C_A U_A \right],
\]
(4.11)

which will enable the utility to cover its costs. This is a very flexible strategy.

4.3 Results

The results of two hypothetical scenarios are shown in Figures 2 and 3.
In Figure 2, economic conditions are favourable and new customers are given
subsidised access to electricity at a moderate rate. Many customers also begin using
alternative energy sources, but this loss of income does not affect the utility because
the overall size of the higher tariff groups expands and its income actually increases.
If the utility were to redistribute its profit among its customers, it would be able to
lower its tariffs or provide “negative” grid fees in the form of basic monthly subsidies.
This is an ideal situation, since it allows for a significant increase in the number of
customers using alternative energy before the utility is in any danger of experiencing
financial difficulties.
By contrast, Figure 3 illustrates the possible consequences of a weaker econo-
my. In this example, too many new customers are given subsidised energy, while
few customers are increasing their energy demands and moving into higher tariff
Figure 2: Tariff structures under favourable economic conditions: $\beta_2 = 0.002$, $\beta_3 = 0.002$, $\beta_4 = 0.01$. 
Figure 3: Tariff structures under unfavourable economic conditions: $\beta_2 = 0$, $\beta_3 = 0$, $\beta_4 = 0.02$. 
groups. This problem is compounded by the fact that many high tariff customers are switching to alternative energy and there are fewer customers left to cover the cost of the subsidised energy.

If the utility depends on external funding to cover these costs, the amount of money required will increase steadily over time and is likely to become unsustainable in a poor economic climate. Applying either of the other two tariff strategies results in a greater financial burden on the high tariff customers and causes a death spiral.

4.3.1 Other significant parameters

In this hypothetical example, several parameters other than the strength of the economy have the potential to alter the results significantly.

The minimum threshold for the price of alternative energy \( S_m \), and the rate of change of \( S(t) \) are the main factors that determine how quickly the utility will lose customers to alternative energy sources. A decrease in either of these quantities increases the likelihood of a death spiral.

The parameter \( \gamma \) represents the inconvenience barrier which prevents customers from switching to alternative energy even when it makes financial sense to do so. This is very difficult to estimate, as it is a combination of many different factors. For example, the time needed to research, purchase and install the necessary equipment might cause customers to choose to continue to use the utility’s energy even if it is slightly more expensive. However, it is important to note that even high \( \gamma \) values will have little effect if the utility’s prices become too high.

The parameter \( G_m \) plays a similar role, but remains significant regardless of the utility’s tariffs. This parameter represents the number of customers who cannot switch to alternative energy sources. These customers may have entered into long-term contracts with the utility or may be prevented from using alternative energy due to constraints imposed by their location or activities.

5 Conclusions

The current pay-per-usage tariff structures used by many utilities are inherently problematic because they are unable to guarantee the income required to maintain the utility’s infrastructure during periods of low energy demand. In the past, the generation of energy has required massive investments of time, money and expertise that were far beyond the reach of the average energy consumer. The utility model was practical in this context: generating energy on a large-scale was both cheaper and safer, and the pay-per-usage tariff structure ensured that the utility was able to cover its costs without charging households and small businesses exorbitant maintenance rates.

Recent developments have made it feasible for both individuals and industry to dramatically reduce their utility bills by supplementing their energy consumption with renewable energy sources, and utilities must find a way to compensate for the drop in revenue. A death spiral may result if the utility responds by increasing its tariffs, which further incentivises customers to seek out alternative sources of energy.
In these circumstances, the pay-per-usage tariff structure is no longer a fair way to recover the utility’s costs. Customers who have access to alternative energy generally remain connected to the energy grid and are able to make use of the utility’s energy whenever they need it, but they contribute very little to the maintenance of the grid infrastructure. The nature of the service that the utility provides to these customers has changed dramatically: instead of being a provider of energy, the utility is now a back-up plan for when alternative energy fails and a convenient channel through which these customers are able to sell their excess energy back into the grid. The pay-per-usage tariffs are no longer sustainable, and the utility needs to implement a new tariff structure that more accurately reflects the different types of services that it provides.

The situation in South Africa is complicated by the fact that major infrastructure expansion is still needed to provide universal reliable access to energy. This generally involves providing subsidised energy to certain customers, which creates additional expenses that must be covered by customers paying higher tariffs. Even if the utility does not suffer a loss in revenue due to alternative energy sources, a death spiral could still occur if the costs of new infrastructure and subsidies grow more rapidly than the number of customers who are able to pay higher tariffs.

On the other hand, current demand for electricity often exceeds the available supply, placing the grid infrastructure under an unsustainable amount of pressure and often resulting in load shedding. For this reason, the utility actively encourages customers to switch to alternative energy sources in order to reduce their demand for energy. However, if too many customers move to renewable energy sources, the utility may exit the industry in the long-run.

The tariff group model has shown that the state of the economy is an important factor in determining the survival of the utility. A strong economy is likely to result in more households and businesses moving into higher tariff groups, which will provide sufficient funding to continue subsidising access to cheaper energy. In this scenario, a significant number of customers may begin using alternative energy without causing a sharp drop in revenue.

A weaker economy will likely result in increased dependence on subsidised energy and a smaller pool of high tariff users. The utility is likely to experience a loss in revenue if a portion of the high tariff customers decide to switch to alternative energy. The utility can use a number of different options such as external funding or grid fees to reduce the risk of a death spiral, but the long-term success of these measures is not guaranteed unless the economy recovers or the utility becomes more efficient.

6 Further work

The model derived in this work can be developed further in order to better represent the real-world situation. In reality, there are many kinds of utility companies but only one type has been considered. A distinction between business and household customers should also be identified. The method for calculating tariffs is more
complicated than described in this work. The location of the customer in relation to the production plant, the intra-day load profile and the number of illegal connections all have an impact on the tariff prices. In this work, renewable energy resources such as solar power were considered. In reality, there are other types of alternative energy sources such as wind, gas and diesel. Some of these sources may be more accessible to larger population groups.

Another strategy to avoid the death spiral, which has not been discussed in this work, is to raise the peak demand tariffs. A more detailed understanding of the structure of tariff pricing would need to be acquired. Based on understanding the tariff structure, different group classifications for the customers would likely need to be adopted.

References


