A system dynamics approach to exploring the relationship between income distribution and residential electricity consumption

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Abstract—The economic health and development of modern economies are dependent on reliable electricity supply, which in turn, is enabled by adequate energy planning and infrastructure investment. Adequate electricity planning can only be achieved through due consideration of electricity demand drivers. Residential electricity demand, coupled to household income, is a significant contributor to electricity demand.

This work reports on a system dynamics study of household income dynamics, including causality with respect to residential electricity demand. Household income dynamics is of particular relevance and importance to South Africa because of the country's relatively high Gini coefficient and progressive redistributive policy measures. The flexibility and feedback dynamics offered by system dynamics provides an insightful alternative to conventional statistical-empirical approaches for exploring such relationships.

The system dynamics model proves a strong correlation between income distribution (Gini coefficient) and residential electricity consumption. Based on a GDP growth rate of 2% per annum, simulation results show that a transition in income distribution or Gini coefficient from 0.67 in year 2012 to 0.5 and 0.4 by year 2035 would result in additional increases in residential electricity demand of 3.1% and 4.7% respectively above the baseline demand growth caused by GDP growth. This dynamic is an important consideration for energy planners since government has (and continues to)

introduce policies and mechanisms to ensure a more equal income distribution and hence a decrease in Gini coefficient.

The system dynamics methodology was demonstrated to be useful in providing insights into changes in present value parameters, such as free basic electricity, fed back as inputs to future behaviour while facilitating causal linkages to other system parameters such as electricity consumption.

Keywords—system dynamics; income distribution; Gini coefficient; residential electricity consumption*

I. INTRODUCTION

Residential sector electricity consumption (largely for lighting and increased appliance usage) continues to grow as incomes increase [1], while increases in incomes are catalyzed by an increased rate of urbanization coupled with industrialization [2]. When residential electricity consumption increases, energy planners are faced with a problem of ensuring that there is adequate capacity to meet the growing demand, especially during morning and afternoon peaks. Relatively expensive peaking power is then deployed when capacity is inadequate for load management [3]. Ideally, implementing energy efficiency measures should assist in closing the energy demand gap, but in every country it remains challenging to rely on these demand side management strategies in instances of inadequate energy planning, especially since energy efficiency saving incentives are transitional measures that work against diminishing returns with a short-term benefit [4]. To support improved planning and system optimisation, therefore, understanding the factors that may affect electricity demand is essential. One of these factors is income distribution.

Income distribution is a particularly important socio-economic policy issue if a society is in need of political stability and sustained economic growth [5,6]. There are many studies which explore the relationship between income inequality and economic growth through statistical empirical research methods. Forbes [7] reported that developed and developing countries with greater inequality have greater economic growth. Barro [8] presents an alternative view and suggests that inequality encourages growth only in rich countries but there is an inverse relationship between inequality and economic growth in poor countries. Either way, empirical data indicates that there exists a linkage between income inequality and economic growth.

Economic growth, in turn, is linked to electricity consumption, with uni- or bidirectional causality being reported, depending on the researcher and the tools they use [9]. It is important to note that although these relationships are described in terms of causality, variables showing positive or negative correlations may not necessarily prove causality as explained by Gujarati [10]: "*Although regression analysis deals with the dependence of one variable on other variables, it does not imply causation…a statistical relationship in itself cannot logically imply causation. To ascribe to causality, one must appeal to a priori or theoretical considerations*." Apparent discrepancies in results between studies could in certain cases be attributed to the methods used, many of which do not model system structure but rather make statistical empirical inferences based on the particular paradigm that is relevant to the study.

This paper explores the use of system dynamics as a decision support tool to provide a better understanding of the causality between residential electricity consumption, income inequality (as measured by the Gini coefficient and the Lorenz Curve) and economic growth to policy makers, energy planners and executive management for the purposes of strategic long-term electricity planning and load management.

II. BACKGROUND

A. ***Income Distribution as Measured by the Gini Coefficient***

Italian Statistician Corrado Gini (1912) introduced the Gini index (also known as the Gini coefficient or Gini ratio) to highlight income inequalities. It measures the extent to which the distribution of income (or consumption) among individuals or households within a country deviates from a perfectly equal distribution [11]. The Gini coefficient is a measure between 0 and 1 where 0 indicates an equal distribution of income amongst all individuals and 1 implies that a single individual receives all the income [12]. This can also be expressed in the form of an index that ranges between 0 and 100. The calculations and interrogation of the Gini coefficient dynamics is usually through statistical empirical analysis [13, 14]. There are many forces that drive economic inequality within communities and countries, with a certain degree of overlap between these. Kaasa [15] provides a detailed list of such forces, which includes demographic, macroeconomic and political factors, in addition to economic growth and the overall development of the country. South Africa has one of the highest Gini coefficients in the world [16]. IHS Global Insight Southern Africa calculated the Gini coefficient at 0.68 in 2002, while the 2011 figure was calculated as 0.63 by the South African Institute of Race Relations (SAIRR) [17].

B. ***Income Distribution and Residential Electricity Consumption***

Many studies indicate that as household income increases, electricity consumption increases due to a migration of household members away from pure necessities and basics to recreational and luxury consumption, particularly for lower income households. However, this relationship is not linear; instead, Engel curves for energy (inferred for electricity) expenditure resemble S-curves where household spending on energy increases or stagnates (or even declines) when income reaches a certain level [18]. Higher income households, although financially able to purchase more expensive appliances than lower income households, would probably be more biased towards energy efficient products and household energy saving measures [19], thus saturating at an earlier level of electricity consumption. Overall, however, increased equality in incomes results in higher average income levels and hence increased consumption.

*C. **Tools to Explore and Understand Income Distribution***

Many methods have been used to explore the correlation between the factors affecting income inequality and the Gini coefficient; including multiple regression analysis and principal component analysis. Multiple regression analysis provides information on correlated variables but results in multi-collinearity (non-measurable factors) whilst principal component analysis makes it possible to reduce the data sets by grouping a large number of similar variables together [15]. Factor decomposition has also been used [20]. These methods all allow for a linear statistical empirical approach to establishing the relationship between factors that affect income distribution.

System dynamics was originally conceived of in the mid 1950's by Professor Jay Wright Forrester (ex-Chair at the MIT's Sloan School) [21] and was identified as an alternative methodology to understand the sensitivities and impacts of different driving forces that affect income distribution since:

- It offers a transparent parameterised causality structure which provides better understanding of the system variables.
- The causality structure allows explicit feedback so that changes in present value parameters, such as free basic electricity, feed back as inputs to future behaviour while facilitating causal linkages to other system parameters such as electricity consumption.
- It allows for sensitivity analysis to be conducted determining which variables influence the overall system in a significant manner, and allows assessment of scenarios to support the understanding of the variables that affect income distribution.

III. METHODOLOGY

The study on which this paper is based [22] commenced with a review on systems thinking, system dynamics modelling and related considerations for energy modelling. Based on the understanding of the literature, the following methodology was adopted for the study:

- A causal loop diagram was constructed to provide a visual representation of the high level dynamics such as urbanization, GDP, demographic development and employment that affect income distribution.
- The System Architecture Map (SAM) was developed to show the overall architecture of flows between variables. This provided an alternative representation of the dynamic modelling variables without the detailed mathematical equations and stock flow feedback diagrams used in system dynamics modelling.
- A model boundary chart with endogenous, exogenous and excluded variables was constructed to explain the constraints and limitations of the model and also to help communicate the boundary of the model and to represent its causal structure. Excluded variables highlighted those causalities not included in the modelling boundary
- The stock flow feedback diagrams were constructed using STELLA® software, along with the relevant equations to be simulated. The two key mathematical relationships that were used in trending the long-term behavior of the system included the logistics curve (where system behaviour was characterised by exponential growth and stabilization towards a non-zero value), and an exponential decay model (assisted with a seamless merging of empirical data trends with modelled data trends). The average household size for the calculations was set at 3.8 members, however this figure is not constant over time, and further work could be done to explore issues affecting population and household size such as fertility, diseases and mortality rates to get a more accurate representation of household sizes in the future. Again, this dynamic is different depending on the different deciles of household income. The scope of this work did not include equivalence scales but this is an important consideration for future work since different household sizes with variable members will contribute differently to household income and expenditure.
- Engagements with stakeholders as well as the comparison of results generated by the simulator with historic results assisted with model validation.

A. ***Causal Loop Diagram***

The CLD (Figure 1) was important in creating a common (generic) qualitative platform for discussion of the perceived thoughts and assumptions that normatively impact income distribution and residential electricity consumption.

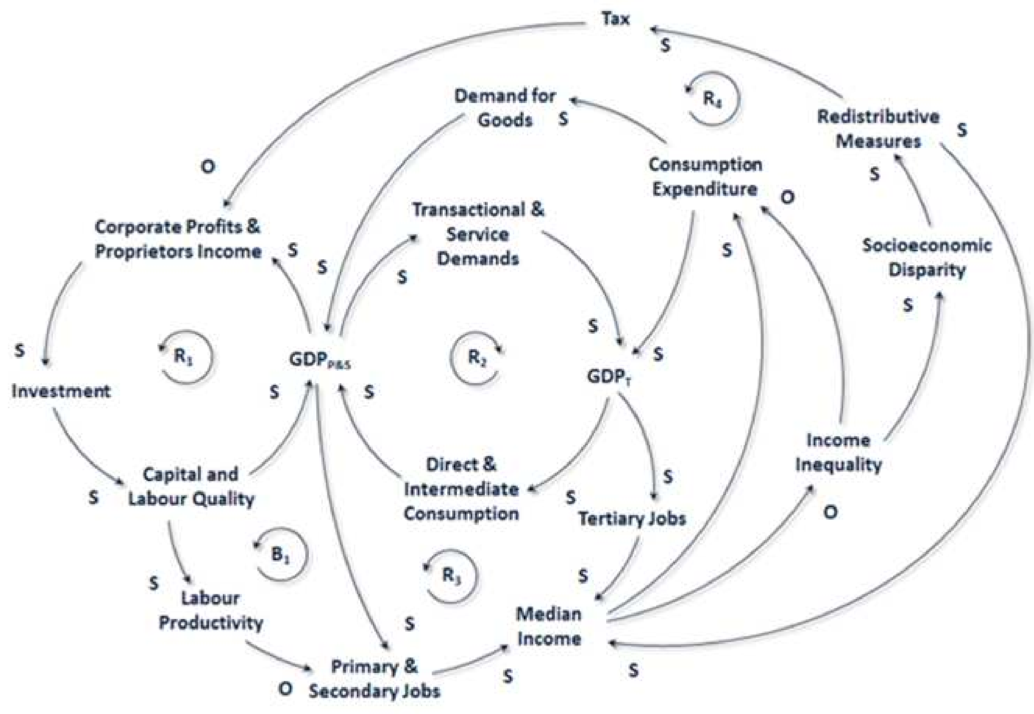

Figure 1. Causal Loop Diagram on Income Distribution Dynamics[1]

The developments of the primary and secondary sectors are capital intensive and require a concentration of wealth to start off. One form of wealth concentration is through corporate profits and proprietor's income (the role of financial services is covered in the tertiary sector).

Wealth concentration enables the investments required for upgrading and maintaining the quality of labour and capital, which in turn increases productivity leading to further growth in the primary and secondary economies. This reinforcing cycle (R1) is an essential element of diversified economies and covers the production elements of only the primary and secondary sector. Demand stems from the consumption by employees (spending wages) and the intermediate demand of goods (consumed in the production process).

The expansion of the primary and secondary sector GDP (GDP_{PS}) leads to an increase in demands for financial services (to facilitate a transactional environment) and for a services sector (both personal services and free labour for specialised economic activities) and to apply knowledge-based services for the improvement of production processes such as research or maintenance. This expansion leads to growth in the tertiary sector and an increase in direct demand for manufactured goods and services

[1] $GDP_{P\&S}$ refers to the GDP in the Primary and Secondary economic sectors while GDP_T refers to the GDP in the Tertiary sector

(affordable through the disposable income of workers in the secondary sector) as well as for intermediate goods (consumed in the tertiary sector economic activities). This reinforcing cycle (R2) expands as a result of surplus production from the primary and secondary sector.

The primary factor in median income is employment. Wage disparity between economic sectors is a secondary influence. Employment (jobs) and average income are affected through several mechanisms:

- Firstly, primary and secondary economy jobs increase as the sectors increase and the same goes for the tertiary sector.
- Secondly, increases in the quality of capital and labour leads to deepening of capital (less labour required in proportion to capital) and a relative decline in primary and secondary sector jobs.

As a primary factor of median income, total employment bears the most direct influence on median income. Median income, together with income inequality leads to an increase in demand for goods and services and an expansion of GDP at the production boundary (personal expenditure needs to saturate to some degree so that further increases in disposable income does not necessarily lead to increased demand for goods and services). Income inequality feeds back into the system in terms of the regulation that socioeconomic disparity exerts through redistributive measures such as social grants and free basic services. These redistributive measures have the effect of adjusting median income while reducing corporate profits and proprietor’s income with a slowdown in growth.

Before evaluating where drivers such as demographics fit into the system, a few feedback loops are identified. Firstly, there is a balancing loop (B1) through the primary & secondary sector system (R1) through one of several mechanisms (split from median Income). Secondly, there is a reinforcing loop (R3) through the primary & secondary sector system (R1) with a branch through the tertiary system (R2). A similar reinforcing loop feeds back directly to median income from GDP_T. Thirdly, there is a reinforcing loop, R4, related to redistributive measures through both R1 and R2 with a split at GDP_{PS}. Using this framework, other relevant drivers and parameters are highlighted.

The CLD was important in creating a common qualitative platform for discussion of the perceived thoughts and assumptions that impact income distribution and residential electricity consumption in South Africa, however, not all aspects were built into the system dynamics simulator.

B. Model Bounday Chart

Table 1 lists exogenous (not affected by the state/ feedback loops of the model), endogenous (dependent on the system state) and excluded (not taken into account in the model) variables for this study.

Table 1. Model Boundary Chart

EXOGENOUS VARIABLES	ENDOGENOUS VARIABLES	EXCLUDED VARIABLES
• GDP growth • Population growth • Free services • Household size	• Gini coefficient • Residential electricity consumption • Disposable income • Electricity	• Government's expenditure and debt • Urbanisation • Level of education • Health of population • Equivalence scales

C. System Dynamics Model Structure

Figure 3 shows part of the model structure that was developed for calculating the household (HH) disposable income and savings per capita per decile.

The first step was to find the parameters for the Gini coefficient variable that could describe a smooth transition with variable rates of change as required for sensitivity analysis of the calibrated Gini trend into the future for data after 2010 (1):

$$Gini = G_0 \times \left(U_0 + \frac{U_1}{1 + \exp[-c(t - t_0)]} \right) \quad (1)$$

Where: G_0 = 0.75 (initial value)

U_0 = 0.68

t_0 = 2040

U_1 = $Gini_{Goal} - 0.68$

c = (-0.10)

It was apparent that since South Africa's Gini coefficient did not follow the classic Lorenz curve (2), it was necessary to develop an exponential growth curve (3) that could be used in combination with the Lorenz curve. The resolution of StatsSA [23] data only allows for a rough numerical integration to calculate the Gini coefficient. It is evident from the Figure 2, below, that using a pure Lorenz curve does not fit the shape of the data well and will result in large interpretation errors.

Figure 2. Fitted Data Compared to a Lorenz Curve

Preliminary calculations showed an error of -1.79 for the modified equation while an error of -7.68 (higher than the actual) was evident for the Lorenz equation (lower than the actual). From previous research completed by Nel [24], the cumulative distribution $k(x)$ was expressed as the linear combination of the Lorenz and the exponential functions (4).

$$L(x) = 1 - \left(1 - \frac{x}{10}\right)^{\left(1 - \frac{1}{m}\right)} \tag{2}$$

$$g(x) = \frac{\left(e^{\frac{-kx}{10}} - 1\right)}{\left(e^{-k} - 1\right)} \tag{3}$$

$$k(x) = (C)g(x) + (1 - C)L(x) \tag{4}$$

Equation 4 was fitted to the Stats SA 2005/6 income and expenditure data with C=0.54735, m=1.2491 and k=4.3283.

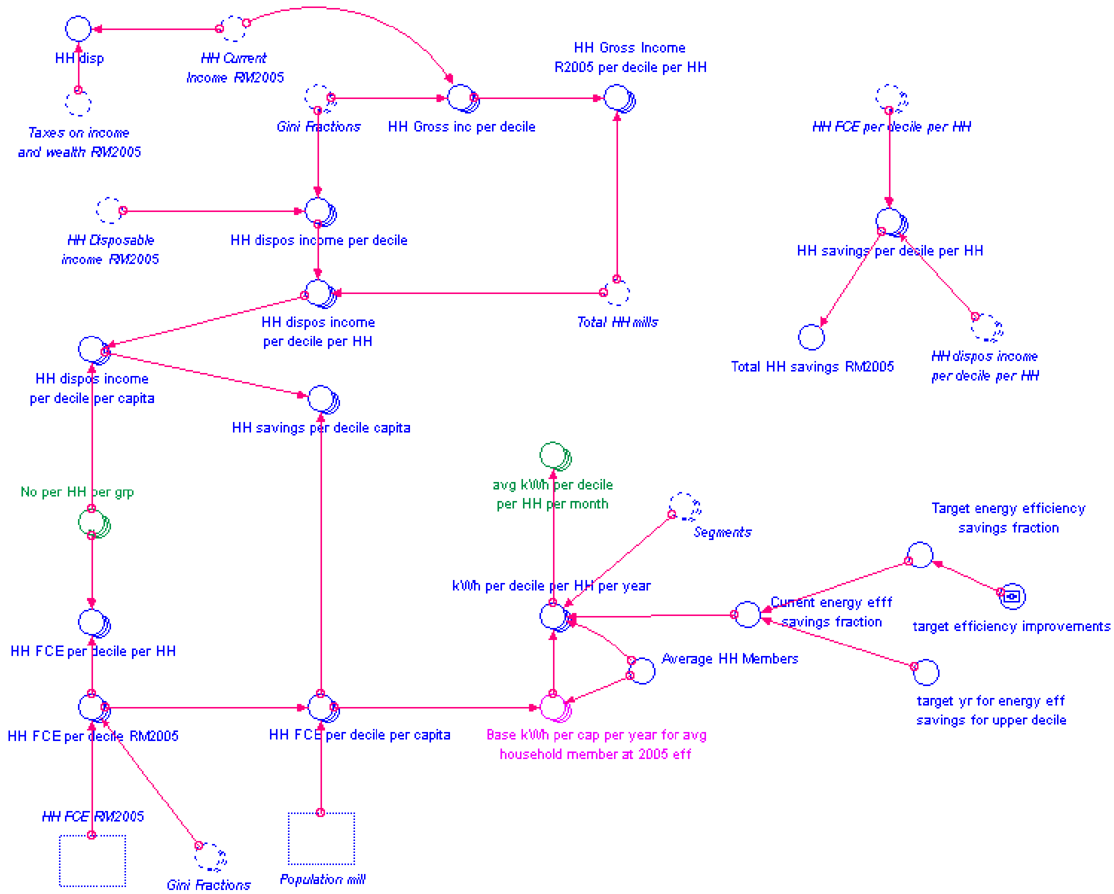

Figure 3: Household Income, Gini Coefficient and Residential Electricity Consumption

The Lorenz-curve parameter m was then used to calibrate variation in Gini distributions from this base, deriving the function in the form shown in (5) for $0.40 \leq G \leq 0.75$:

$$m = 5.1554 \times 10^2 G^4 - 1.24196 \times 10^3 G^3 + 1.1258 \times 10^3 G^2 - 4.5791 \times 10^2 G + 7.2139 \times 10^1 \quad (5)$$

The Gini fractions were then calculated using a Segment(Fraction) arrayed variable and the m value. In using the Gini fractions, HH disposable income per decile was calculated and divided by the average number of people per household (3.8) to work out the HH disposable income per capita per decile. By subtracting the calculated HH Final Consumption Expenditure (FCE) per capita per decile, the HH savings per capita per decile was computed. The Base electricity consumption per year was then calculated (6).

$$Base\ electricity\ consumption\ per\ year = U_0 + \frac{U_1}{1+\exp[-c(v-v_0)]} \quad (6)$$

Where: U_0 = -14023.9

U_1 = 14572.9+14023.9

v_0 = 298.77

v = *HH FCE[fraction] x Average HH members*

c = 5.17×10^{-6}

The final electricity consumption per household per decile per year was then calculated using the Base electricity consumption per year and an energy efficiency savings (modelled for different trend scenarios using S-curves with different c values).

IV. RESULTS

One would expect that with an increase in average disposable household income, the average electricity demand for households would causally increase. The relevant question then being, if it changes, how significant is this change and does it fundamentally affect energy and capacity planning.

To determine the causal relationship between Gini coefficient and residential electricity consumption, GDP growth was assumed to be a constant 2% from 2013 onwards. Please note that for Fig.5 – Fig.8, results were generated using the system dynamics simulator interface in Fig. 4 and thereafter drawn using MS Excel for illustration purposes.

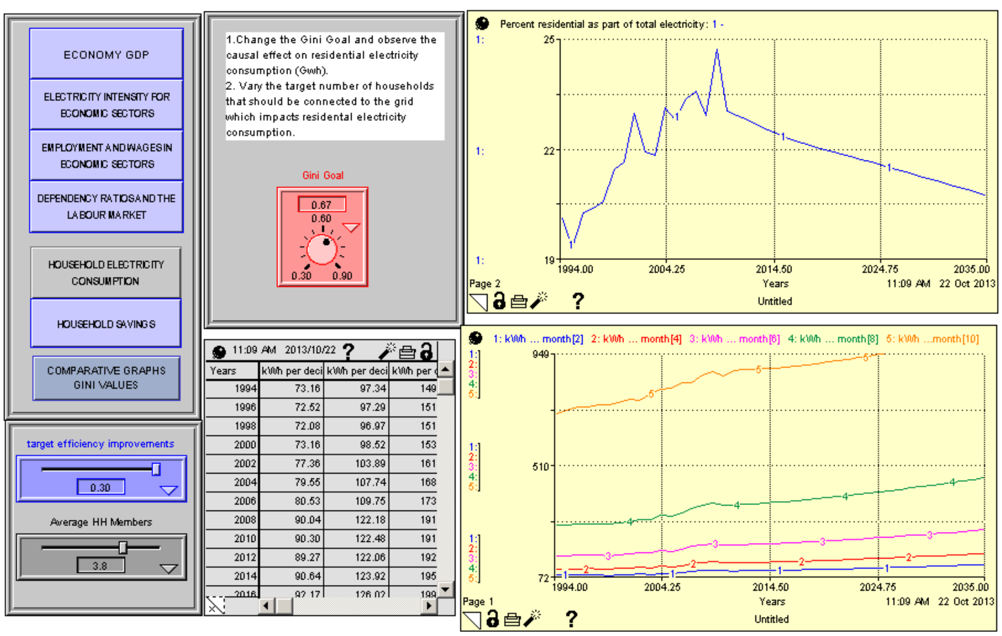

Figure 4: System Dynamics Interface Showing Residential Electricity Consumption

Fig. 5 displays the results of the simulator runs for different values of Gini coefficient.

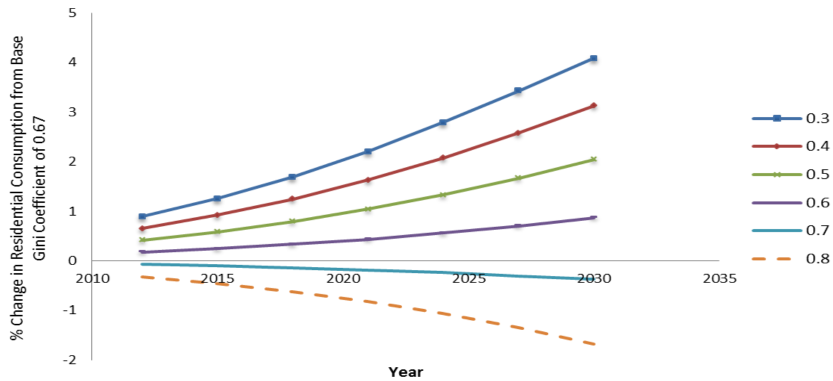

Figure 5: Residential Electricity Consumption with Varying Gini Coefficients

The results in Fig.5 show total residential consumption trends over time, but does not resolve trends in different income groups. The lifestyles within the low income (deciles 1-4), middle income (deciles 5-7) and high income (deciles 8-10) groups differ and contributions towards the electricity component of energy is different (Figs. 6, 7 & 8).

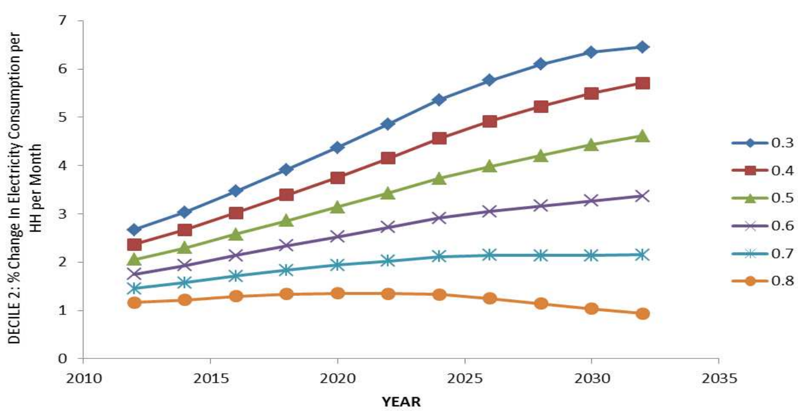

Figure 6. Impact of Changing Gini Coefficient on Residential Electricity Consumption (Decile 2)

Comparative graphs showing the percent change in residential electricity consumption per HH per decile for deciles 2, 5 and then 9 for different runs of Gini coefficient (0.3, 0.4, 0.5, 0.6, 0.7 and 0.8) at a GDP growth of 2%.

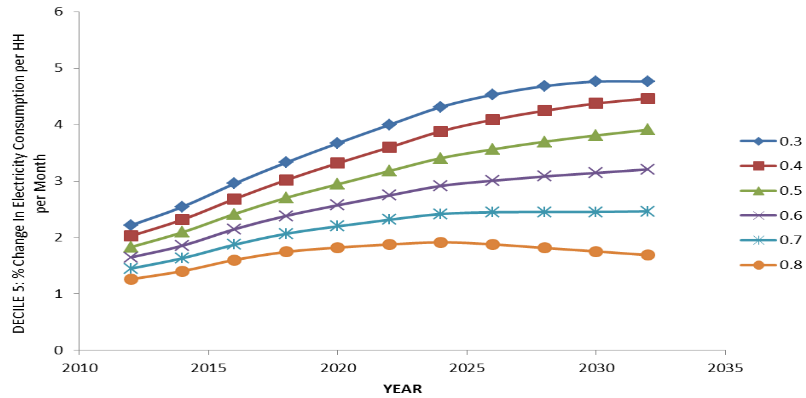

Figure 7. Impact of Changing Gini Coefficient on Residential Electricity Consumption (Decile 5)

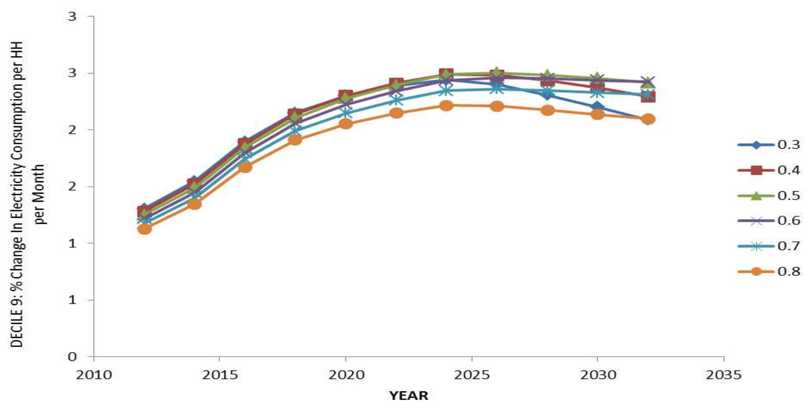

Figure 8. Impact of Changing Gini Coefficient on Residential Electricity Consumption (Decile 9)

From the results, it is clear that a change to a lower Gini coefficient for decile 2 has a significant increased trend in residential electricity consumption while for the higher income decile 9, the increase is marginal.

V. DISCUSSION

The results demonstrate that, as would be expected, changing the Gini coefficient has a direct impact on residential electricity consumption. It is clear that the smaller the Gini coefficient value (the more equal the income distribution), the higher the residential electricity consumption, a result that is critical in future energy planning considerations. A 2% GDP growth rate was selected for scenario analysis in view of the fact that economists have revised the growth outlook in South Africa this year to 2%, 0.2 percentage points lower than August 2013 [25]. The trends in the primary, secondary and tertiary economic sectors were modelled to a best-fit future trend until 2035. It was also assumed that population growth is S-shaped with a goal of 56.8 million by 2035. For a GDP growth rate of 2%, by year 2035, a Gini coefficient of 0.5 implies a 3.14% increase in residential electricity demand while a Gini coefficient of 0.4, indicates a 4.73% increase in residential electricity demand. This dynamic is an important consideration for energy planners since government has (and continues to) introduce policies and mechanisms to ensure a more equal income distribution and hence a decrease in Gini coefficient from 0.67 to lower values.

The lifestyles of the low, middle and high income households differ and contributions towards the change in residential electricity consumption with changing Gini coefficient are different depending on the income group. At a GDP growth rate of 2%, simulator scenarios for lower Gini coefficients show a resultant (and significant) increase in the low income households but a marginal increase in the high income households. For the lower income groups, an increase in average income could result in an improvement in lifestyle and the purchase of electricity consuming appliances, however, an increase in average income for the higher income groups could mean greater contributions towards wealth creation through investments instead of increasing residential electricity consumption, and an indirect economic rebound effect on the economic sectors.

The high income group consumes several times more electricity than the lower income groups but patterns of behaviour over time indicate that this trend tapers off in the long-term. This could be due to the long-term impact on income distribution (depending on which income group is contributing towards the increase in electricity), which will differ after year 2035 since greater investment in creating wealth will again skew the equalisation of income distribution.

It is important to note that the average HH numbers chosen for the scenario analyses have not been linked to equivalence scales which take into account that households have different sizes and compositions and may enjoy economies of scale when sharing resources among HH members (in other words, households with non-working adults would include income only from non-work sources such as government subsidies while households with more than two working adults may generate a larger relative income).

VI. CONCLUSIONS AND RECOMMENDATIONS

System dynamics has been demonstrated to be a useful methodology to explore the dynamics around income distribution, and although the model excluded many factors, the dynamic behaviour of the income distribution system was feasibly represented. The methodology provided an alternative to the more common modelling techniques such as multiple regression analysis and principal component analysis, with a distinct benefit of modelling multiple variable causalities and feedback loops in the system. It is clear, however, that using system dynamics required a thorough knowledge of the key driving forces that impact income distribution, as well as system dynamics as a method to derive quantitative results.

Results show that income distribution has a direct influence on residential electricity demand. In addition to this, average household income is a determinant of general consumption behaviour patterns within deciles and the average residential electricity consumption of the low, middle and high income groups are aggregated to the total residential electricity consumption. Ultimately, if the causality between income distribution and electricity consumption is not considered in energy planning and policy making, it would most likely affect capacity planning and result in a shortage in energy (electricity) required for economic and social development of the country.

Although the model results show comparative trends in long term behavior of household electricity consumption with changing Gini coefficient, they do not include the key drivers for what is causing the change in long term electricity consumption patterns across the low, middle and high income households. More research can be conducted on the electricity price elasticity effects that will drive consumer behavior in terms of energy efficiency and possibly fuel switching.

Further work on the causality and impact of qualifications, education levels and skills development on income distribution, economic growth, entrepreneurship, labour productivity and population growth (with time lag effects is possible). There is also scope for expansion and improvement of the model in the areas such as resolution of excluded parameters including equivalence scales for household members due to different electricity consumption patterns.

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