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## USING AN ADAPTED SYSTEM DYNAMICS APPROACH TO DETERMINE THE LINKAGE BETWEEN ELECTRIC VEHICLE MARKET PENETRATION AND AFFORDABILITY

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### ABSTRACT

This paper focuses on an adapted process for system dynamics modelling based on industry experience and the successful implementation of system dynamics models within an electricity utility. The modelling process was demonstrated using a case study of battery electric vehicle (BEV) market penetration in South Africa and its substitution of internal combustion engine vehicle, as a function of affordability based on real disposable income. The results indicate that South Africans are living beyond their “income” constraints and purchasing far more vehicles than what their disposable income allows, with the situation worsening over time. The Gauteng province will have the largest potential to absorb BEVs (81,123) and the highest impact on residential electricity consumption (an additional 4,291 GWh) whilst the lowest is the Northern Cape province with 5,140 BEVs (an equivalent of 272 GWh). However, if disposable income is used as a parametric to determine the affordability of BEVs then there may be 80% less than the expected number of BEVs in terms of market penetration. To benefit from a reduction in carbon emissions in the transport sector, a renewables heavy supply mix would be required else there is not much benefit with South Africa’s current coal heavy supply mix.

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## 1. Introduction

Eskom, a State Owned Corporation (SOC), is an electricity utility in South Africa, responsible for supplying approximately 96% of the electricity used in the country and more than 45% of Africa [1]. The nature of the utility's operating environment in the context of socio-economic, political and environmental changes requires an evolving business model with a dynamic planning approach [2] capable of understanding feedback behaviour across the electricity value chain [3]. To develop strategically sound business models for economic and environmentally conscious competitive advantage, advanced modelling tools and processes are required [4],[5].

Experience and extensive engagements between the organisation's stakeholders and the System Dynamics Centre at Eskom SOC resulted in an adapted system dynamic modelling process for the successful implementation of simulations to tackle complex system problems. This paper explains the conventional high-level modelling process and then the adapted system dynamics modelling process, using the results from the *E-StratBEV* system dynamics simulator. The *E-StratBEV* was developed to determine the linkage between battery electric vehicle (BEV) market penetration and affordability, based on disposable income in South Africa.

## 2. Energy Modelling Approaches

Mathematical energy modelling tools, focussed on the energy-economy-environment nexus, have been critical in support of strategic business model development [6]. There are numerous energy modelling methods, however, the main categories include econometrics [7], macro-economics [8], multi-criteria decision analysis [9], optimization [10] and simulation [11], [12]. The most applied simulation and modelling methods includes agent-based modelling, discrete event modelling and the system dynamics process [13]. System dynamics modelling was identified as being useful in strategy refinement and the transfer of insights as part of strategy implementation [14].

The system dynamics modelling process advocated by Sterman [15] was initially used as a standard framework for developing system dynamics models by the Eskom System Dynamics Centre, but this modelling process gradually evolved with experience gained through stakeholder engagements, which contributed to the successful implementation of the adapted system dynamics process within the power utility [16].

### 2.2 System Dynamics Modelling

System dynamics is characterised by a computerised approach, based on systems thinking principles and was founded by Forrester in the 1970s, who applied engineering concepts of feedback systems and digital simulation to understand "*the counterintuitive behaviour of social systems*" [17]. The type of problems, which require a system dynamics approach, would be those that have quantities that change over time and are dynamic in nature, and those which have feedback [18]. The system dynamics modelling process uses the premise that every real system, including business environments, could be explained in a mathematically-based approach using a series of equations, represented by interconnected flows or rates and storage levels (stocks). This is represented by Equation 1, where the state variable is the stock, which is based on the difference between the rate of change of the inflow and the outflow, where  $dt$  is the time interval for each computational step.

$$stock(t) = stock*(t - dt) + (Inflow - Outflow)*dt \quad (1)$$

The system dynamics modelling process requires several steps, as shown in Figure 1 [19].



Figure 1: System Dynamics Modelling Process [19]

Following a detailed modelling process prevents the modeller from conceptual problems, and provides the necessary contextualisation of the system problem to be modelled.

### 2.3 Review of System Dynamics Modelling Processes

A summary of the conventional system dynamics modelling processes is provided in Table 1, with a list of sub-elements constituting each step.

**Step 1: Problem Identification and System Conceptualization:** This step includes defining the problem dynamically with or without the use of data, since the behaviour of a system variable over time follows a pattern that can be illustrated [19]. After identifying the problem, key variables and reference modes (historical data or patterns of behaviour of variables); feedback structures are identified. For this purpose, causal loop diagrams [20] illustrate the visual cause-effect and loops of role-playing variables related to the system problem [21]. Part of this step includes a clear model purpose. Sterman [15] refers to this step as *Problem Articulation*, which also includes defining time horizons.

**Step 2: Model Formulation:** This includes formulating rate equations and defining the variable parameters and initial values. Coyle [22] included influence diagrams in the second step, and Sterman [15] included various other tools, such as a model boundary chart (which indicates which variables are endogenous (outputs), exogenous (inputs) or excluded in the model structure), a sub-system diagram, a causal loop diagram, stock and flow maps and policy structure diagrams. The causal loop diagrams or system diagrams may be constructed by group model building, a facilitated participatory modelling method whereby stakeholders are guided through a brainstorming session to determine as many variables and relationships of these variables linked to the system problem [23].

**Step 3: Model Testing and Further Development:** Understanding model behaviour and sensitivity runs, refinement and reformulation, as well as validation, characterise this step. The iterative nature of the modelling process is emphasised where the iterations depend on the complexity of the system problem being modelled. Sensitivity analysis is based on 3 main categories: numerical (if parameters change with numerical values) [24], behavioural (model behaviour and pattern over time changes when parameters change) [25], and policy sensitivity (checking model runs against policy-based conclusions) [26].

**Step 4: Policy Analysis:** At this stage, sensitive policy parameters are identified, the ones which result in the most change in influencing the system and would tend to be the areas to be leveraged, besides the feedback loops which dominate system behaviour [27].

In Eskom SOC, the first system dynamics simulation was developed in 2010 and presented to the company's Executive Committee and Board of Directors, as part of a scenario-planning project. The simulation proved advantageous in understanding the underlying system structure through scenario analysis, to challenge and even change previous mental models, as identified by Schoemaker [28]. Over the last five years, it became apparent that the acceptance and successful implementation of system dynamics models relied on the modelling process followed with stakeholders, the effectiveness of engagements as well as the identification of non-intuitive leverage points. The adapted system dynamics modelling process resulted in several system dynamics models being implemented after development, and bridges the gap between model development and successful implementation and execution of the models. This paper explains each of the steps in the adapted system dynamics modelling process using a case study of electric vehicle market penetration in South Africa's provinces and its substitution of internal combustion engine vehicle (ICEV), as a function of affordability based on real disposable income.

Table 1: Summary of Steps in a System Dynamics Modelling Process

SOURCE	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5
Richardson & Pugh III, 1989 [19]	<p><b>Problem identification and system conceptualization:</b> Define the problem, model purpose, list key variables and reference modes, and causal loop diagrams.</p> <p><b>Problem articulation:</b> Define problem, key variables, time horizon, and historical reference modes.</p>	<p><b>Model formulation:</b> Rate equations and variable parameters.</p>	<p><b>Model testing and further development:</b> Sensitivity runs, refinement, and validation.</p>	<p><b>Policy analysis:</b> Dominant feedback loops, and the most sensitive parameters identified.</p>	-
Sterman, 2000 [15]	<p><b>Dynamic hypothesis:</b> Identify theories around hypothesis, model boundary chart, sub-system diagram, causal loop diagram, stock and flow maps, and policy structure diagrams.</p>	<p><b>Formulation of the model:</b> Specify structure &amp; rules, estimate parameters, and test for consistency with model purpose.</p>	<p><b>Testing:</b> Compare to reference modes, and robustness in extreme conditions.</p>	<p><b>Policy Formulation and Evaluation:</b> Specify scenario, what if and sensitivity analysis, and determine synergies between policies.</p>	-
Randers J. , 1976 [21]	<p><b>Conceptualization:</b> Definition of question asked, real-world behaviour, system boundary through feedback loops (CLD), and identifies system descriptors.</p> <p><b>Problem recognition:</b> Who cares, and why.</p>	<p><b>Formulation:</b> Detailed model structure, and parameter specification.</p>	<p><b>Testing:</b> Model assumptions, and model behaviour sensitivity to policies.</p>	-	-
Coyle, 1996 [22]	<p><b>Problem understanding and system description:</b> Develop influence diagrams.</p>	<p><b>Qualitative analysis:</b> Innovative ideas, and theories.</p>	<p><b>Simulation modelling:</b> Use of software, and includes model testing.</p>	<p><b>Policy testing &amp; design:</b> Sensitivity testing resulting in insights and policy optimisation.</p>	-

### 3. ADAPTED SYSTEM DYNAMICS MODELLING PROCESS

Eskom SOC developed an Integrated Strategic Electricity Plan (ISEP), which includes complex dynamics such as increasing generation availability alongside generation expansion, ensuring a financially and environmentally sustainable business, and a consolidation of socio-economic contributions to ensure economic development in the country and in Africa [29]. These documented complexities require extensive time to read through and filter out salient points so that mental models can be established by decision makers, based on perceived contextualisation. Mental models are unique to the individual and based on their theoretical knowledge, business experience and intuitive deductions [30].

Various modelling methods and processes are used to support the development of the organizational strategies [14]. System dynamics was introduced as an additional modelling process, incorporating group model building which could provide causal linkages and feedback loops for hundreds of variables and provide understanding of the system problem by allowing various sensitivity and scenario analysis [26].

The adapted eight step system dynamics modelling process includes some group model building elements [31] including system conceptualization, model formulation and decision making, with an emphasis on those practical aspects of project scoping, model communication and knowledge transfer necessary for the implementation of models and modelling solutions (Figure 2).

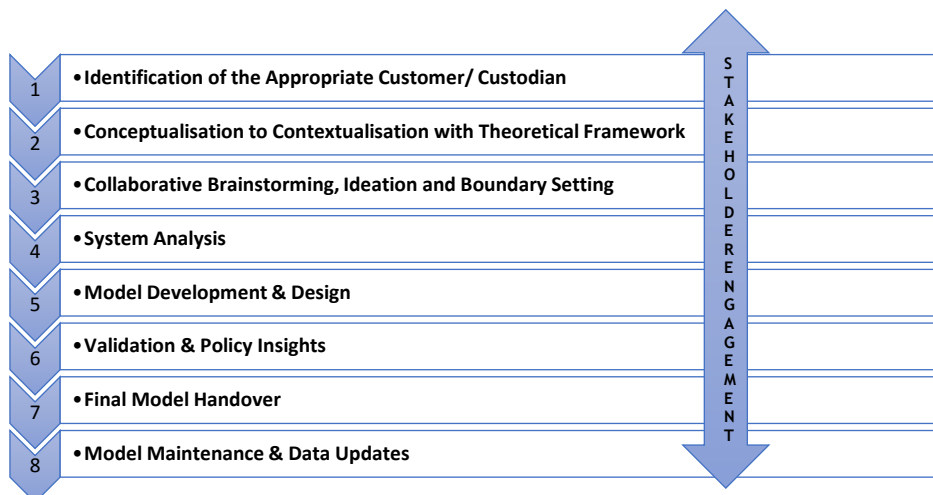


Figure 2: Adapted System Dynamics Modelling Process

#### 3.1 Identification of the Appropriate Customer/ Custodian

A project may be initiated by a customer or be proposed by a system dynamicist (based on their experience, technical knowledge and understanding of the company's corporate objectives and business priorities). If the system dynamicist proposes a system dynamics model for development, they identify a potential custodian who is on an executive level with sufficient business influence. The custodian then nominates a technical owner who would be trained in using the completed tool, running the relevant scenarios and reporting the results to the senior decision makers. Generally, the initial challenges for a system dynamicist is being presented with broad scopes to deliver on specific results using a system dynamics model.

The system dynamicist has to engage with stakeholders (sometimes on multiple occasions) until a focused question is defined to address a particular business system problem. Generally, the customer has conceptualised what they think should be developed through their mental models but experience difficulty in contextualising their ideas and formulating a focussing question. For customers/custodians with no prior system dynamics knowledge, successfully completed system dynamics tools are presented

to the potential customer, relevant to their business interest with a discussion of how the results from the tools have been used for strategic cost benefit analysis or enhanced system understanding for improved decision making. Part of this step also involves identifying an interdisciplinary work group to engage with on a regular basis. The work group members could consist of the system dynamicist, the custodian and or customer, technical engineering members, environmentalists, financiers, subject matter experts etc.

### 3.1.1 Case Study

This study was initiated by the system dynamicist after discussions with external stakeholders (Postgraduate University supervisors) and proposed to the company. It was approved by the company, as sponsored further studies, since it aligned with the company's business strategy and corporate plan. This paper focusses on the approach which was taken to develop the simulator known as E-StratBEV, which was used to run scenarios and determine the linkage between BEV market penetration and affordability based on disposable income.

## 3.2 Conceptualisation to Contextualisation with the Theoretical Framework

In supporting the customer to contextualise the project requirements, they are advised to suggest typical graphical outputs or variables they would like to understand by running the model. This does not prescribe a preconceived result in terms of the emergent model solution since the trend or graphical result may be non-intuitive and unexpected but it allows reflection on the system variables which may have to be reported on, and establishing a focussing question. Part of contextualising includes establishing a suitable modelling timeframe. The timeframe provides insight in determining the resolution of data which would be required. Depending on the resolution of data, different data owners or workgroup members are identified for further liaising.

### 3.2.1 Case Study

The following focusing question and objectives were established for the BEV study:

**Table 2: Focusing Question and Objectives of the Battery Electric Vehicle Study**

Focusing question	Objectives
How does disposable income affect the affordability in the residential sector and market penetration of BEVs in South Africa?	<ul style="list-style-type: none"> <li>To develop electricity supply and demand side sub-modules, with a focus on the residential sector electricity consumption profile.</li> <li>To factor in income distribution and consumer affordability causally with residential electricity consumption</li> <li>To determine the charging requirements of BEVs after ICEV substitution and the related carbon emissions on a provincial level.</li> </ul>

The timeframe for the simulator was 2015 [32] until 2050, to coincide with the timelines for the Green Transport Strategy [33], and the Integrated Energy Plan [34]. The South African provinces included the Eastern Cape province, the Free State province, Gauteng province, KwaZulu-Natal province, Limpopo province, Mpumalanga province, North West province, the Northern Cape province and the Western Cape province.

The system dynamicist then constructed a diagrammatic framework based on the operational and theoretical information linked to the system problem being modelled. This framework illustrated the high level system architecture map of the system problem and the related environment, in support of problem contextualisation (Figure 3). It did not display cause and effect relationships or directional quantities linked to the variables but included important upstream and downstream variables, driving forces and externalities specific to that environment. The value of such a map is that it helped with engaging with

the stakeholders on a first pass and proved to be very effective. It assisted the system dynamicist in acquiring the necessary basic system problem understanding on a more technical level since it required extensive literature reviews before it could be constructed. It was, thereafter, through engagements, verified by the customer as being the correct final framework meeting the project specification. This step required high level assumptions to be agreed upon and possible proxies where no data was available for quantitative mathematical equations.

### 3.2.2 Case Study

In Figure 3, the electricity supply and demand modules were developed and then used to determine the reserve margin. The supply module comprised of various generation options (fossil fuel, nuclear, gas, hydro, renewables) and was used to calculate the carbon emissions within the coal heavy supply mix. The vehicle module was made up of BEVs (requiring electricity for charging) and ICEVs (which also contributed to carbon emissions). The disposable income in the residential sector was used to calculate vehicle affordability whilst various drivers were linked to the BEV module to assess influences on BEV market penetration.

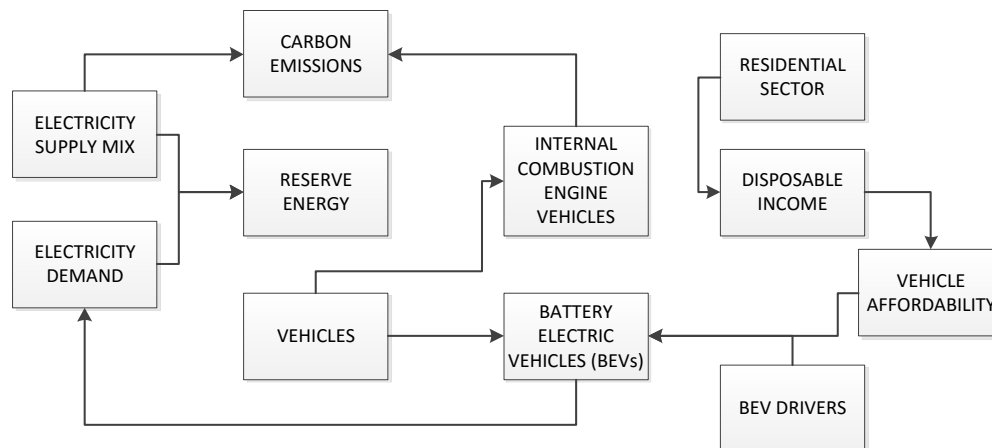


Figure 3: System Architecture Map

### 3.3 Collaborative Brainstorming, Ideation and Boundary Setting

This step is consultative and involves a group of role players, some of whom were identified to be part of the work group team in prior steps. The constitution of this collaboration and ideation team is critical and relates back to group model building exercises [23] since the output can be fairly subjective i.e. developing a causal loop diagram (CLD). The quality of subjective outputs such as the CLDs depend largely on the collective knowledge and experience of the participants hence the emphasis on carefully selected participants. The system dynamicist facilitates the interactive and carefully managed session and directs the discussion around those aspects related to the system problem, by steering the group clear of emotionally charged arguments. This process is usually started by using sticky notes, one per variable, and through group discussions the causal linkages are made between the variables on the sticky notes. The CLD is usually finalised in a follow up session with the group after the system dynamicist completes the first draft. CLDs may be revised and be part of an iterative dynamic process over the life of the project. At this stage, the system dynamicist is equipped with a very clear idea of the variables that would be included in the model boundary chart. The stakeholder discussions also help finalise the assumptions necessary for further work and those variables which may be excluded due to the required customer-defined project scope.

### 3.3.1 Case Study

Figure 4 illustrates the CLD for the BEV case study. For a big electricity supply-demand gap, the supply increases to close the gap, which then also results in less supply required (*Electricity Supply-Demand: Balancing Loop 1*). The Gross Domestic Product (GDP) served as a proxy for the economic health of the country. When the economy experiences growth (in the services, transport, agriculture, forestry and fishing, industrial sectors), the gap between supply and demand of energy becomes smaller. When the gap gets smaller, the GDP may be influenced by balancing factors which slow down economic growth (*Economic Growth: Balancing Loop B2*). In South Africa this supply is met by the predominantly coal-based base load. An increase in GDP usually results in employment which supports the drive to a more equal income distribution. In the residential sector, this means more average real disposable income per household. An increase in real disposable income means consumers can afford purchasing motor vehicles, which supports transport sector growth and the overall economy (*Income Distribution: Reinforcing Loop R1*). An increase in ICEV sales results in more carbon dioxide emissions. In the national drive to decarbonize our environment, an increase in carbon emissions in the transport sector incentivizes consumers to purchase more electric vehicles. The introduction of BEVs increases the demand for electricity required for charging and increases the supply-demand gap (*Transport Sector: Reinforcing Loop R2*).

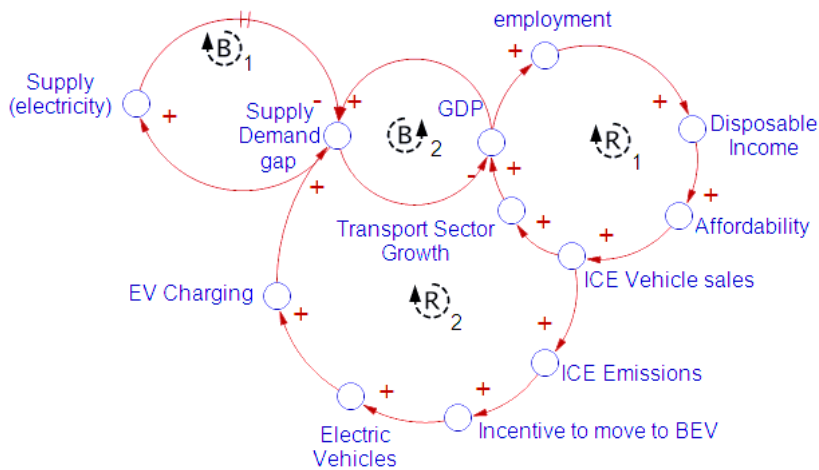


Figure 4: Causal Loop Diagram

The Model Boundary Chart (MBC) (see Table 3) lists the exogenous, endogenous and excluded variables for this study.

Table 3: Model Boundary Chart

EXOGENOUS VARIABLES	ENDOGENOUS VARIABLES	EXCLUDED VARIABLES
<ul style="list-style-type: none"> <li>Electricity supply Options (MW)</li> <li>Residential electricity demand (GW)</li> <li>Disposable income (R)</li> <li>BEV import taxes (R)</li> <li>Registered ICEVs (Number)</li> </ul>	<ul style="list-style-type: none"> <li>Carbon Emissions (Mtons)</li> <li>BEV charging requirements (kWh)</li> <li>Affordable BEVs (Number)</li> </ul>	<ul style="list-style-type: none"> <li>Infrastructure</li> <li>Weather</li> <li>Politics</li> </ul>



### 3.4 System Analysis

Experience has shown that there are many organizational misconceptions that the system dynamics modelling software constitutes the system dynamics modelling process. The reality is that significant time should be spent on problem identification and contextualisation, as well as data and system analysis, before commencing with the structural design of the system dynamics model. The analysis could include statistical methods or programmable codes to determine patterns or relationships or simply involve a process of ordering and simplifying both qualitative and quantitative data into a time resolution suitable for importing into the system dynamics model. The empirical data may have gaps which may require classical regression, time series decomposition, least squares approximation, numerical interpolation or exponential smoothing or a combination of data analysis techniques. Perpetual linear growth trends are dismissed on the premise that real system elements have biophysical constraints and if the appropriate time period has been selected, these trends tend to plateau and reflect the carrying capacity of the system. This step is also critical since it can help the system dynamicist establish if any integration errors or incorrect structural linkages have been made which may result in large variances in the results once the modelling software is used. Preliminary calculations have also assisted in the initiation and development of smaller system dynamics models, which have been used as stand-alone tools for some customers.

#### 3.4.1 Case Study

In this study, due to the huge volume of hourly BEV data, preliminary data mining was necessary to filter the 2015 BEV data obtained from the Eskom-Nissan BEV pilot study [35] so sub-routines (MS Excel Macros) were written to allow filtering and ordering of the data before further mathematical computations. The historic real disposable income on a national level was used to determine the future trend nationally using Equation 2, where  $x$  is time.

$$\text{Future Real Disposable Income} = -27.165 \times x^3 + 1,732 \times x^2 - 4,824 \times x + 888,155 \quad (2)$$

### 3.5 Model Development & Design

The model structure may be designed to represent component configurations on the power plant, causally and mathematically linking the variables identified in the CLD, the MBC and the system architecture map. Once the model has been developed, the Beta version is usually handed over to the model owner and customer. They engage with the interface and run various scenarios, a process which does not require in-depth knowledge of the model structure. It has been found that only when the model is run by the model owner, do they fundamentally tune into the model and pick up elements which they would like to have changed, despite having various demo's by the system dynamicist during previous meetings. The additional "tweaking" and refinement of the simulation is then concluded.

#### 3.5.1 Case Study

The empirical number of registered ICEVs per year in the South African provinces was obtained [36] from year 1999 until 2017 and an S-curve (Equation 3) was built into the model structure to determine the future trend of actual ICEVs until year 2050 shown in Figure 5.

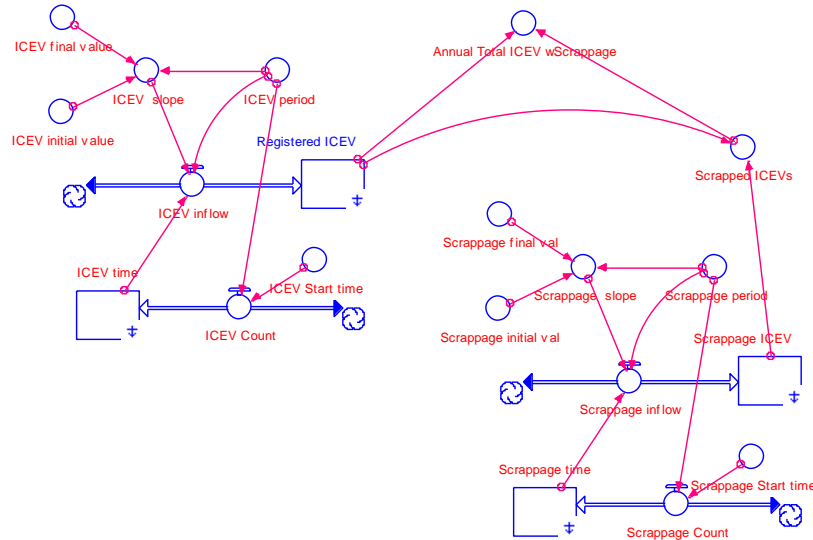


Figure 5: Model Structure of Actual Motor Cars

Equation 3 allows for asymptotic conversion to lower values, by specifying a negative value for  $U_1$ , or a positive stabilizing non-zero value by retaining a positive value for  $U_1$ .

$$P(t) = U_0 + \frac{U_1}{1 + \exp[-c(t - t_0)]} \quad (3)$$

where  $P$  is the dependent variable and  $P(t)$  is a function of time  $t$ ;  $U_0$  is the zero offset;  $U_1$  is the ultimate increase (or decrease) above  $U_0$ , modelled using a S-curve;  $c$  is a growth rate exponent that determines the maximum slope of the S-curve; and  $t_0$  is the time at which the maximum slope is reached (inflection point).

The scrappage rates built into the structure obtained from derivations by Bento et al. [37] using data from 1987 to 2014 and the average vehicle age. For this study an average vehicle age of 11 years was used [38] and a corresponding scrappage rate of 13.84%.

Once the actual ICEVs per province was calculated, the average monthly income per proportion of households with a motor vehicle was used to calculate the affordable number of ICEVs using the percentages in Table 4, sourced from the South African Institute of Race Relations [39]. The percentages were applied for all the provinces however, the disposable income and the number of households were specific to each province.

Table 4: Monthly Income and Proportion of Households with ICEVs

Monthly Income Category	Proportion of Households with a Motor Vehicle
Up to R799	2.8%
R800-R1 399	4.5%
R1 400-R2 499	2.9%
R2 500-R4 999	9.3%
R5 000-R7 999	20.7%
R8 000-R10 999	44.7%
R11 000-R19 999	75.2%
R20 000	145.3%

Source: Van Heerden [40]; IRR, Eighty20, Xtract based on AMPS [39] 3723-10

The gap between the actual and affordable ICEVs was linked to an ICEV Correction Factor which accounted for the umbrella of influences e.g. vehicle financing schemes, which result in consumers purchasing more ICEVs than they should be able to afford.

The target number of BEVs was 233,700 BEVs from 2019 until 2040 for South Africa using the GDP parametric (South Africa's GDP is on average 0.0057 of the world GDP), and a global BEV target of 41 million by 2040 [41]. GDP was used to make the provincial distributions due to BEVs still being classified as luxury goods, if drivers and incentives were already in place to make BEVs more affordable then disposable income could have been used as a measure. Thereafter BEV substitutions with the actual ICEVs were made on a provincial level and the resulting impact on residential electricity consumption and carbon emissions calculated. The ICEV Correction Factor was used to adjust the BEV market penetration to what the affordable number per province was expected to be.

### 3.6 Validation & Policy Insights

In this step, the final validation of the model is carried out. Besides the work group members, any internal and external parties with an interest in the model are contacted to run through the model scenarios and calibrate according to experience and new information which may emerge, a process which allows for theoretical and empirical consistency checks [42][43]. Empirical consistency includes comparing the simulation results to historical data and ensuring closeness of fit. Validation is also carried out by evaluating other models, results and assumptions on related work and comparing the project results.

#### 3.6.1 Case Study

Figure 6 shows the difference between the actual and affordable number of ICEVs in 2015 and expected in 2030 and 2050. Gauteng province has the highest average difference between Actual and Affordable ICEVs by 2050 (4.252 mill), followed by the Western Cape province (1.545 mill) and KwaZulu Natal province (1.174 mill). All the other provinces have smaller differences between the Actual and Affordable ICEVs (between 0.108 mill and 0.519 mill). The reasons for this difference could include access to many readily available vehicle finance schemes such as balloon payments (which allows for reduced monthly instalments for the period of the credit agreement with an inflated final instalment due to the capital amount not being settled), fixed interest rates (credit agreement linked to the dynamic change in the prime interest rate) and instalment sale agreements (credit agreement that allows consumers to spread the capital amount plus interest over a set period).

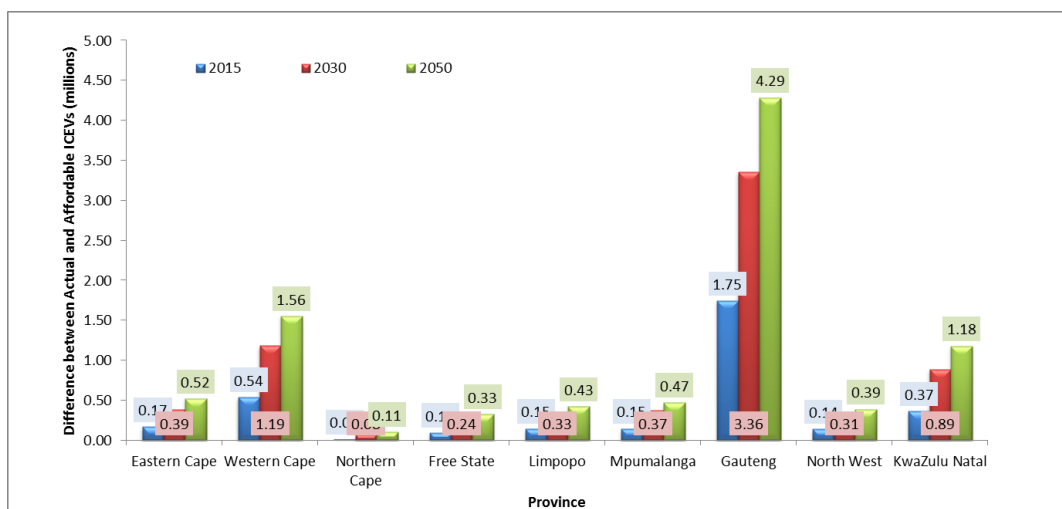


Figure 6: Provincial Distribution of ICEVs (Actual and Affordable) per Province

Figure 7 shows the BEV distribution per province after substitution with ICEVs and then after adjusting with the ICEV Correction Factor to obtain an expected number of BEVs based on affordability. Gauteng province would be expected to have the highest number of BEVs (81,123) followed by KwaZulu Natal (37,220) and the Western Cape (32,220).

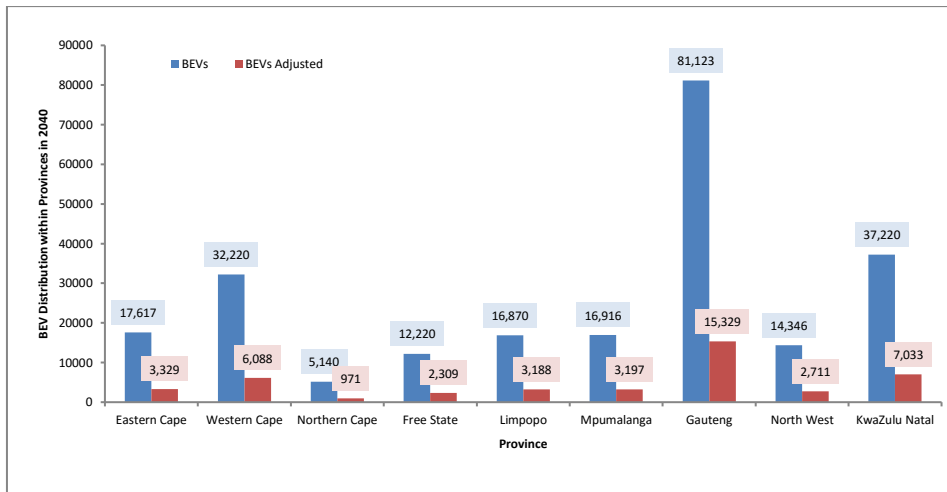


Figure 7: Provincial Distribution of BEVs with Adjustments Based on Affordability

The adjusted BEV distributions were about 80% less than the direct substitution with ICEVs based on original target.

Figure 8 shows the impact of the BEVs on the residential electricity consumption. Gauteng province has the highest BEV impact on residential consumption (adding an additional 4,291 GWh), followed by KwaZulu Natal province (an additional 1,969 GWh), then the Western Cape (an additional 1,704 GWh).

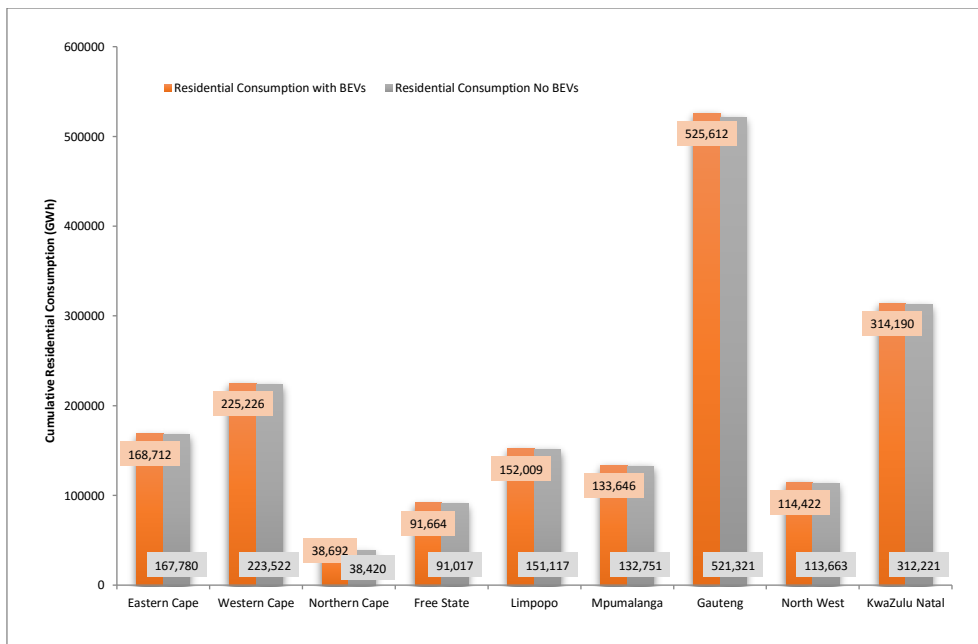


Figure 8: Cumulative Residential Electricity Consumption (2019-2040)

The cumulative change in carbon emissions from 2019 until 2040 was calculated on a provincial level, Table 5.

**Table 5: Cumulative Change in Carbon Emissions (Mton) from 2019 - 2040**

Province	Energy Sector	Transport Sector
Eastern Cape	0.39	-0.34
Free State	0.28	-0.19
Northern Cape	0.13	-0.18
Western Cape	0.70	-0.80
Gauteng	1.80	-2.00
KwaZulu Natal	0.78	-0.65
Limpopo	0.41	-0.20
Mpumalanga	0.39	-0.30
North West	0.35	-0.21

The net effect in terms of carbon emissions increasing in the energy sector and decreasing in the transport sector is negligible, most likely due to the carbon heavy supply mix and the fact that emissions calculations in the transport sector were from tank to wheel and not well to wheel.

### 3.7 Final Model Handover

The model handover stage is a formal step to ensure that the simulation results are checked against the original scope of the project and have been completed. Various training sessions are arranged with the model owner to ensure independent running of the model. The handover stage is officially minuted and signed off by the system dynamicist and the customer. Post the handover stage, the customer generally identifies additional minor model changes or additions which could enhance the optimal running of the tool.

#### 3.7.1 Case Study

For this study, the *e-StratBEV* was handed over to the Eskom eMobility team to use in further scenario analysis.

### 3.8 Model Maintenance & Data Updates

If the amendments identified by the customer, post the final handover stage, require significant structural model changes, then a new project is again started, however, if the changes are minor such as data updates or quick model changes, then these are covered under Model Maintenance. A record is kept of the date of model completion and the interval dates/frequency when the maintenance should take place. This step minimizes potential frustration the customer's side and ensures long term use of the tool.

## 4 CONCLUSIONS

The adapted system dynamics modelling processes, which included elements of group model building necessary for strategy implementation, proved to be an effective and rigorous modelling process for the practical development and implementation of system dynamics tools for use in an electricity utility. Certainly, although the modelling method provided some quantitative insights into regional variations of the impact and expectations of BEV market penetration in South Africa, it still provides more value if used for exploratory modelling and descriptive comparative scenario analysis as opposed to predictive system behaviour down to the last decimal place.

Looking at the gap between actual and affordable vehicles, nationally, it would appear that South Africans are living beyond their “income” constraints and purchasing far more vehicles than what their disposable income allows, with the situation worsening over time, due to mechanisms encouraging consumers to live on credit, such as vehicle finance schemes. The results indicate that the Gauteng province and the Western Cape province have the largest potential to absorb BEVs (and the highest impact on residential electricity consumption) whilst the lowest is Limpopo province, based on GDP distributions. Future projects to build BEV charging infrastructure should consider these dynamics. To benefit from a reduction in carbon emissions in the transport sector, a renewables heavy supply mix would be required.

## 5. ACKNOWLEDGEMENTS

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