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Using a System Dynamics Modelling Process to Determine the Impact of eCar, eBus and eTruck Market Penetration on Carbon Emissions in South Africa

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Abstract: The complexities that are inherent in electricity value chains are non-linear in nature and they require unconventional modelling methods, such as system dynamics. This paper provides an overview of the system dynamics method applied for obtaining an understanding of the impact of electric-bus, -car, and -truck market penetration on carbon emissions in South Africa, through the development of the electric mobility simulator (eMobiSim). Two scenarios were tested. The World Reference scenario was based on a market penetration of 22% eCars, 19% eTrucks, and 80% eBuses and the Gross Domestic Product (GDP) scenario was based on 2.38% eCars, 1.79% eTrucks, and 12% eBuses. The results indicate that the World Reference scenario is the most optimistic, with a 12.33% decrease in carbon emissions in the transport sector and an increase of 4.32% in the electricity sector. However, if the economic structure that is specific to South Africa is to be considered and the GDP scenario is run, then there would only be a 1.77% decrease of carbon emissions in the transport sector and an increase of 0.64% in the electricity sector. Although the eCar market penetration produces the highest reduction in carbon emissions, the volumes that are required are large and other factors, such as price parity and affordability in the various income deciles, would have to be considered in determining whether this volume is achievable.

Keywords: electric vehicle penetration; battery storage; carbon emission

1. Introduction

Electricity utilities face many new pressures, such as stricter environmental legislation, ageing infrastructure, changing energy mixes, cyber security demands, and load management [1]. These challenges have stimulated discussions and strategies around new business models that can accommodate the transitions in organizational and financial architecture to ensure value-added energy services to customers in a sustainable manner.

South Africa faced both institutional and political barriers preventing widespread access to electricity in the late 1980s; however, policy shifts resulted in infrastructural development and programmes that supported a growth in electrification rates [2]. Recent challenges have required a shift from traditional business models to non-standard approaches due to the convergence of factors, such as the emergence of new technologies, economics and investment decisions, public policy, deregulation, new competitors, and the introduction of renewable energy sources [3]. Some of the new emerging technologies include advanced analytics, artificial intelligence, new generating technologies, and electric vehicles, all of which will impact the operating environments of utilities.

The changes in the operating environments of these electricity utilities challenge the application of linear programming techniques due to the complex interactions between variables within the socio-economic, political, and technical mesh of their evolving business environments [4,5]. This non-linearity, together with time delays require advanced modelling methods that are capable of understanding feedback behaviour across the electricity value chain [6], to provide competitive advantage [7,8].

Various modelling methods were reviewed, such as agent-based modelling and diffusion-rate models [9]; stochastic models and Monte Carlo methods [10]; TIMES-based modelling [11]; and, mixed-integer linear programming before commencing with this study to understand the relative impact of electrifying cars, trucks, and buses on electricity demand and carbon emissions in South Africa [12]. Many of these models include quantitative dependencies, which appear to be able to handle deterministic equations, by integrating multiple variables in a complex system environment. Unfortunately, these models lack the ability to represent the full context of the problem, since they do not incorporate feedback, delays, and non-linearity [13], with an ability to highlight unintended consequences.

The Green Transport Strategy [14], which was developed by the South African national Department of Transport, has focused on a national plan to mitigate against climate change while considering efficient integrated transport systems and electric vehicle technologies, in view of South Africa's pledge to reduce greenhouse gas emissions (GHG) by 42% by 2025 [15]. Although the measures include modal shifts from private vehicle use to public transport, as well as an emphasis on electric passenger vehicles (eCars), insufficient information is available regarding the (potential) impact of electric buses (eBuses) and electric trucks (eTrucks) market penetration on reducing carbon emissions. A key objective of the paper is then to quantify the impacts of electric vehicle (EV) penetration and their relevance in South Africa to reach its GHG target based on global EV trends and taking the economic structure of the country into account. A second objective is to present an adapted system dynamics modelling process that is relevant for electricity utility operations. Simulation computer modelling using system dynamics was identified as a suitable method for capturing the dynamic context of this study. However, the conventional system dynamics approach was further adapted with elements of group model building [16] to ensure an effective and rigorous modelling process for the practical development and implementation of system dynamics tools for use in an electricity utility system dynamics model, which is referred to as the Electric Mobility Simulator (eMobiSim) [17], to determine the impact of electric vehicle market penetration on carbon emissions in South Africa.

The paper will explain the detailed adapted system dynamics methodology, followed by the application results of the methodology to the case study of the impact of electric vehicle market penetration on carbon emissions. This will be followed by the results and discussion section, and then the conclusions.

2. Methodology

The conventional system dynamics modelling process includes problem articulation, model formulation, model testing, validation, and policy analysis [18] (Figure 1); while, the adapted eight-step system dynamics (SD) modelling process (Figure 2) that was followed in this study, including system conceptualization, model formulation, and decision making, with elements of group model building.

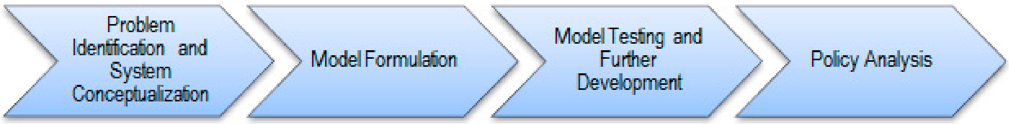


Figure 1. The Conventional System Dynamics Modelling Process [18].

Figure 2. The Adapted Eight-Step System Dynamics Modelling Process [19].

The difference between the conventional modelling process and the adapted process is that the latter provides emphasis on the practical aspects of project scoping, model communication, and knowledge transfer necessary for the implementation of models and modelling solutions. The extension of completed system dynamics models into the implementation and execution phase for sustainable scenario analysis filled the process gaps, and further distinguished it from the conventional system dynamics modelling steps. Each of the steps in the adapted system dynamics modelling process will be explained below.

2.1. Project Inception

The project inception step included identifying a potential custodian on an executive level with sufficient business influence to ensure the acceptance of the modelling approach. The custodian then nominated 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. A part of this step also involved identifying members to form a work group to engage with on a regular basis. The work group consisted of the system dynamicist, the custodian/customer, technical engineering members, environmentalists, financiers, and subject matter experts.

The initial challenges for the system dynamicist of being presented with broad scopes to deliver on specific results while using a system dynamics model, as is the case with conventional SD modelling, was resolved through establishing a focussing question to address a particular business system problem. Establishing the focussing question required multiple customer engagements, since some stakeholders conceptualised their perceived requirements through their mental modelling (A mental model is defined as a "representation of some domain or situation which supports understanding, reasoning and prediction" [20]), but experienced difficulty in contextualising their ideas into a specific focussing question. In this step, various points were emphasised to the customer and relevant stakeholders:

- The model would not be predictive but descriptive, and the results would not be accurate to the last decimal point; however, value would be obtained through understanding the factors that affected the patterns of behaviour of the graphical trends, so that leverage points could be identified to effect change and impact the system positively.
- Although validated empirical data should be used to calibrate the model, experience and tacit knowledge could also be used, so the need for subject matter experts in the working group would be critical.

- The model should not be used to prove a biased or preconceived outcome with respect to emergent system behaviour, since the emphasis should be on a mathematically sound model that represents the system as closely as possible.

2.2. Concept to Context

The customer was supported with contextualising the project requirements through establishing a suitable modelling timeframe, which provided insight in determining the resolution of data that would be required. Depending on the resolution of data, different data owners were identified for further liaising or workgroup members. The system dynamicist then constructed a diagrammatic framework, which is known as a system architecture map (SAM), based on the operational and theoretical information linked to the system problem being modelled. Although the SAM did not provide quantitative directional linkages, it contextualised the upstream and downstream variables within the system. Proxies were used where no data where available for quantitative mathematical equations. The development of a SAM was effective in providing stakeholders with a "birds-eye" view of the system problem being modelled and provided a simple framework for explaining the context of the system.

2.3. Boundary Setting

Boundary setting was critical in preventing project scope creep, and also to balance model complexity with the right level of understanding. A collaboration and ideation team was identified, relating back to group model building exercises [21], so that causal loop diagrams (CLDs) could be developed.

The system dynamicist facilitated the interactive and carefully managed session and directed the discussion around those aspects related to electric vehicles and environmental aspects, by steering the group clear of emotionally charged arguments. The CLDs were revised and part of an iterative dynamic process over the life of the project. The stakeholder discussions also helped in finalising the assumptions that are necessary for further work and those variables that may be excluded due to the required customer-defined project scope. The SAM and the CLDs both provided a deeper understanding of the system problem, depending on the stakeholder's visual and interpretive learning styles.

A part of this step involved identifying the exogenous (not affected by the state/feedback loops of the model) and endogenous variables (dependent on the system state), which would be part of the model and determining the historic behaviour of these variables, so that future trends could be mathematically formulated based on previous data.

2.4. System Analyses

Significant time was spent on problem identification and contextualisation, as well as data and system analyses, before commencing with the structural design of the system dynamics model. The analyses included statistical methods and programmable codes to determine the patterns or relationships between variables.

Perpetual linear growth trends were dismissed on the premise that real systems elements have biophysical constraints and it helped the system dynamicist to establish whether any integration errors or incorrect structural linkages were made, which could otherwise have resulted in large variances in the results once the modelling software was used.

2.5. Model Development and Design

The model structure was designed to causally and mathematically link the variables and elements discussed in the SAM and CLD, while using iSee Stella Software [22]. Rate equations were formulated and initial variable parameters were established for the stock-flow-feedback structures developed, based on the "Principle of Accumulation", as illustrated in Figure 3. The "converter" takes input data for conversion into output data, generally through mathematical formulation. The "flow" represents the rate at which the stock will change at any instant in time. The "cloud" represents stocks that lie outside the model boundary.

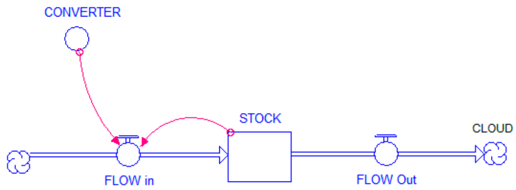


Figure 3. Illustrative Stock Flow Diagram [13].

Equation (1) was used in the model structure, which determines that the Stock at time t is found from the Stock at a previous point in time, $(t - dt)$, by adding the net quantity that accumulated as the result of the inflow and outflow during the period *dt.*

$$Stock\ (t) = Stock(t - dt) + (Inflow\ Rate - Outflow\ rate)\ \times\ dt \quad (1)$$

Feedback loops control the behavior of a system over time. Reinforcing loops cause exponential growth or decline, while balancing loops cause goal-seeking behavior, and they have a quantity that will grow rapidly for a while and then slow down, as it converges in on its goal. Various balancing feedback loops were built into the simulator.

The iSee Stella software used in developing the system dynamics model also allowed for an engagement platform to be built, whereby the customer can interact with the model and run scenarios.

2.6. Policy Insights and Validation

Validation was an ongoing process and it involved contacting stakeholders to run through the model scenarios and calibrate the model according to experience and new information that emerged. This step included conceptual [23], operational validity, and empirical data validity [24]. Conceptual model and operational validation was carried out by ensuring that the scope and level of detail of the model was adequately representative of the system problem and would have been able to address the objectives of the study. Empirical data validity involved comparing the simulation results to the measured data and ensuring a closeness of fit. The validation process also involved extensive engagements with stakeholders who have experience in particular areas, if research or actual data was unavailable.

2.7. Model Handover

The model handover stage was a formal step for ensuring that the simulation results were checked against the original scope of the project and was completed. Various training sessions were arranged with the model owner to ensure the independent running of the model.

Once the model was developed, the first "Beta" version was handed over to the customer to engage with and to run various scenarios, a process that did not require in-depth knowledge of the model structure. It was found that only when the model was run by the model owner did they pick up elements, which they wanted to change. The additional changes to the simulation model structure was then concluded.

2.8. Model Maintenance and Updates

A new project would have been started if amendments that the customer identified, post the final handover stage, required significant structural model changes. However, if the changes were minor such as data updates or quick model changes, so these were covered under Model Maintenance.

3. Application of the Methodology to the Case Study

3.1. Project Inception

The project custodian for this study was a program lead for the electricity utility's eMobility project. Members to form a work group to engage with on a regular basis consisted of the system dynamicist, the custodian, technical engineering members that are involved in eMobility projects in the utility, environmentalists, and subject matter experts outside of the utility involved in EV studies.

The focussing question for this study was: "What is the impact of electric vehicle market penetration on carbon emissions in the transport and electricity sectors in South Africa by 2040?".

3.2. Concept to Context

For this study, the simulator timeframe started to be able to understand the historical trends of variables and to establish mathematical equations in 1993, which could then be used to simulate future behaviour over time. The end of the simulation timeframe was 2040, which fell within the timelines for the Green Transport Strategy [14] and the Integrated Energy Plan [25].

Figure 4 shows the SAM for this study. South Africa's current electricity supply is heavily reliant on coal-fired power stations (resulting in carbon emissions in the electricity sector), although the generation mix is evolving to include renewables generating options.

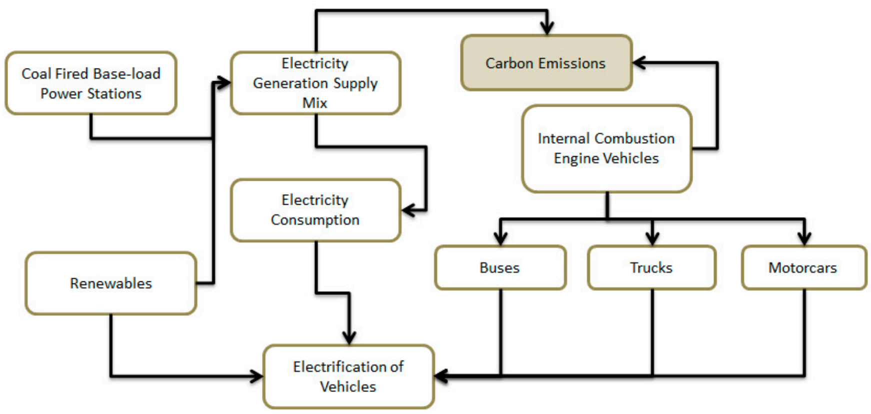


Figure 4. The System Architecture Map.

Carbon emissions in the transport sector have also contributed 10.8% of the national Greenhouse Gas (GHG) emissions [26]. This has encouraged efforts to improve the efficiency of the internal combustion engine vehicles (ICEVs) and look at electrification technologies. The electrified vehicles (buses, trucks, and motorcars) require electricity, which is sourced through renewables (solar charging) or through the current electricity generation mix for the charging infrastructure.

3.3. Boundary Setting

Figure 5 shows the CLD for the study. The "B" represents a balancing loop. A balancing loop shows a current state of the system and a move towards a desired state or goal.

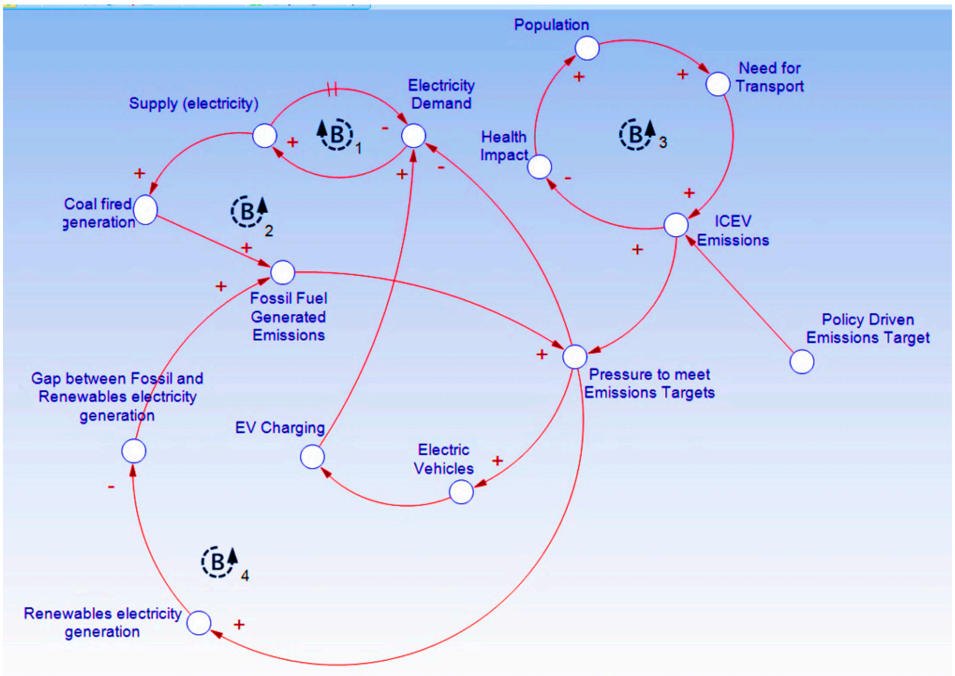


Figure 5. Causal Loop Diagram.

Balance of Supply & Demand (Balancing Loop 1)**:** An increase in electricity demand, due to sectoral economic growth, results in an increase in electricity supply. Over time, the electricity supply decreases having met the initial demand, thus reducing future demand.

Emissions Targets (Balancing Loops 2) & Closing the Gap with Renewables (Balancing Loop 4): An increase in electricity supply requires more base-load electricity generation, which contributes to fossil-fuel generated emissions. This negative environmental impact results in carbon taxes and increased pressure to meet emissions targets, which effectively reduces the overall electricity demand. The pressure to reduce emissions also results in a concerted effort to increase the renewables share in the electricity generation mix, which reduces the gap between the fossil and renewable electricity generation, and the overall fossil generated electricity.

Transport Needs (Balancing Loop 3): As the population increases, urbanization, economic growth and the need for commuting and transport increases. An increase in transport means that the current fleet of ICEVs will generate carbon emissions in the transport sector and impact on health, which might result in deaths and a reduction in the overall population.

The ICEV emissions are subject to policy driven emission targets, which require a reduction in emissions. ICEVs are then substituted with EVs, which require electricity for charging. The electricity consumption due to EV charging then again increases the demand for electricity.

3.4. System and Data Analyses

Raw data for the electric cars were obtained from a three year joint study between the electricity utility and an electric car manufacturer [27]. The study involved capturing data, such as distances travelled, times EVs were charged, weekend versus weekday charging profiles, and electricity consumption for 10 electric cars. Microsoft Excel was used to trend the hourly demand profiles in the electricity utility, as well as the electric car charging and consumption profiles. Figure 6 shows the average consumption and charging profile for July 2015. Similar data were analysed and collected for the electric car pilot period extending from 2014 until 2016, and then aggregated into an annual resolution so that it could be used to exogenously input into the system dynamics model.

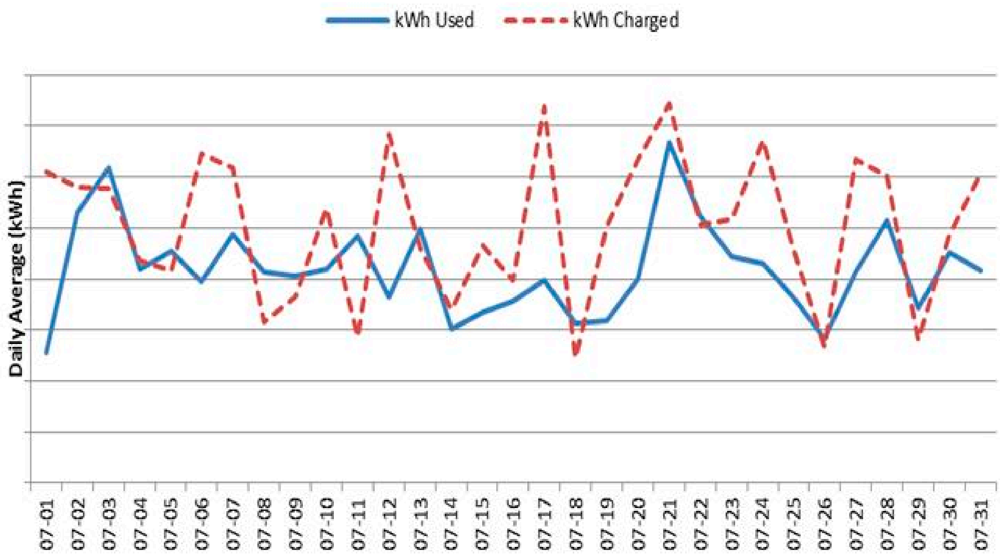


Figure 6. Daily Consumption and Charging of Electric Cars for July 2015 [27].

From the empirical data analysis, the average daily fuel consumption was 14.1–21 kWh per 100 km with an average daily distance of 71 km. Some of the empirical data had gaps, which required classical regression to detemine the missing data in registered ICEVs based on historical trends, e.g. the regression equation for determining the ICEV trend for the Eastern Cape province is shown in Equation (2):

$$y = 411.73x^2 - 1948x + 252084 \quad (2)$$

Perpetual linear growth trends were dismissed on the premise that real systems elements have biophysical constraints and it helped the system dynamicist to establish whether any integration errors or incorrect structural linkages were made, which could otherwise have resulted in large variances in the results once the modelling software was used. Many of the model structures used the logistics curve equation specified in Meyer [28], as shown in Equation (3), which allows for asymptotic conversion to lower values, by specifying a negative value for U_1, or a positive stabilizing non-zero value and keeping 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 while 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).

3.5. Model Development and Design

Equation (3) was built into the model structures to calculate the future trends of the variables. Figure 7 is one of the model structures built using iSee STELLA software, where a goal seeking target value for eTrucks results in a ubstitution with the ICEV version and then a revised number of ICEVs are calculated.

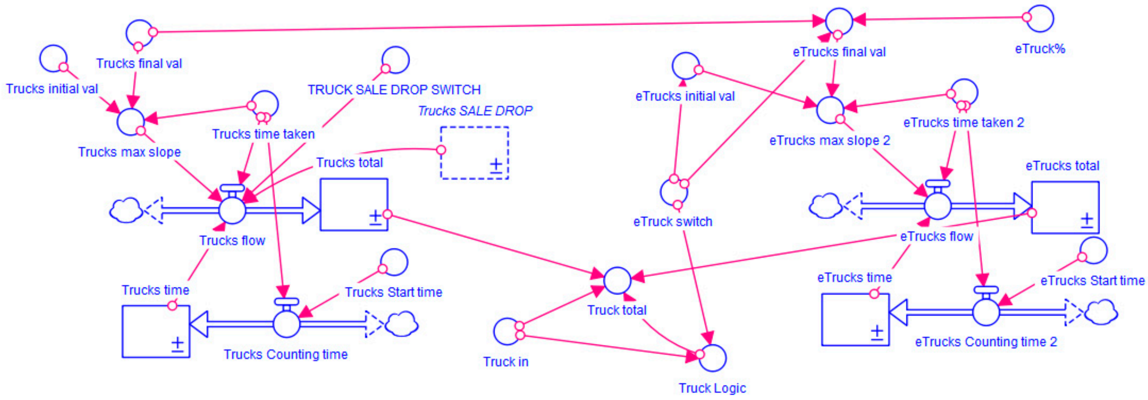


Figure 7. Stock-flow Model Structure.

Similar model structures were built to calculate the future trends for state variables, such as the quantity of each vehicle category and the electricity demand per province. Endogenous variable calculations were made for calculating the carbon emissions from the generating plants and the transport sector per province. Time series data for the South Africa's future coal baseload future capacity was aligned to the IRP 2016 [25] plan, while the existing power generation supply sub-module included capacities for the coal power plant fleet, nuclear, hydro-pumped storage, gas cycle turbines, hydro-electric power, and wind power [29].

3.6. Validation

The validation of the structure and key variables in the eMobiSim was through stakeholder engagement with researchers undertaking projects that were linked to eMobility within the organisation, besides obtaining expert opinion validation through demonstrations and engagement with executives from the uYilo e-Mobility Programme. Assumptions on variables, such as percent charging at home, driver impact sensitivity, EV targets, and affordability, were discussed and used to calibrate the models parameters. Other research organizations, such as Electric Power Research Institute, were also engaged with on assumptions and the structure of the model as well as results. Parameterization of time series data, when there was insufficient empirical history was through regression analysis. Historical and future trends in the supply and the demand modules were compared to historical operational planning trends that were completed by departments within the utility.

4. Results and Discussion

4.1. Scenarios

South Africa does not have any targets for the number of electric trucks and buses expected by year 2040; hence, literature scans were conducted to establish the international targets being evaluated and these were then used to run scenarios for the South African context.

(a) World Reference (WF) Scenario

The first scenario (known as the World Reference scenario) used the following values for the electric vehicle market penetration by 2040:

- 19% eTrucks (70,709) by 2040 based on the Electric Vehicle Outlook 2019 report by BNEF [30],
- 80% eBuses (51,100) by 2040, indicated by Colin McKerracher, the lead analyst on advanced transport for BNEF [31].
- The 22% eCar target was based on the South African Government's Green Transport Strategy, published by Department of Transport, which plans for three-million electric vehicles by 2050 [16]. This would equate to a target of 2.39 million EVs by 2040 while using an S-curve to find the value at year 2040.

Based on the World Reference scenario, the number of electric vehicle sales to be expected to meet the targets by 2040 is as follows in Table 1:

Table 1. Expected Annual electric vehicle (EV) Sales to Meet the Targets in the World Reference Scenario.

World Reference Targets (WR) by 2040	**19%**	**80%**	**22%**
Year	eTrucks WR	eBus WR	eCar WR
2020	584	422	0
2021	1169	845	23,902
2022	1753	1267	47,804
2023	2337	1689	71,706
2024	2922	2112	95,608
2025	3506	2534	119,509
2026	4091	2956	143,411
2027	4675	3379	167,313
2028	5259	3801	191,215
2029	5844	4223	215,117
2030	6428	4645	239,019
2031	5844	4223	215,117
2032	5259	3801	191,215
2033	4675	3379	167,313
2034	4091	2956	143,411
2035	3506	2534	119,509
2036	2922	2112	95,608
2037	2337	1689	71,706
2038	1753	1267	47,804
2039	1169	845	23,902
2040	584	422	0

(b) GDP scenario

The second scenario uses Gross Domestic Profit (GDP) to determine the number of electric vehicles. South Africa's GDP is on average 0.0057 of the world's GDP, and an increase in luxury goods purchases (such as electric vehicles) appears to positively correlate with an improvement in economic conditions within a country [32]. Using the GDP parametric, the following electric vehicle market penetration values were calculated for South Africa based on global EV sales forecasts by Bloomberg New Energy Finance (BNEF) [31]:

- 1.2 million eTrucks globally, corrected by the GDP factor would be 6 840 eTrucks (1.79% of the SA truck fleet).
- A 20% share of the global bus fleet in 2019 is equivalent to 400,000 eBuses; thus. an 80% share by 2040 is likely to be 1.4 million, corrected by the GDP factor, this would be 7980 eBuses (12% of the SA bus fleet).
- 56 million passenger eCars globally by 2040, corrected by the GDP factor would be 319 200 eCars (2.38% of the SA passenger car fleet).

Based on the GDP scenario, the number of electric vehicle sales to be expected to meet the targets by 2040 is, as follows, in Table 2:

Table 2. Expected Annual EV Sales to Meet the Targets in the GDP Scenario.

GDP EV Targets by 2040	**1.79%**	**12%**	**2.38%**
Year	eTrucks GDP	eBus GDP	eCar GDP
2020	54	63	0
2021	109	125	3192
2022	163	188	6384
2023	217	251	9575
2024	272	313	12,767
2025	326	376	15,959
2026	380	439	19,151
2027	434	501	22,343
2028	489	564	25,535
2029	543	626	28,726
2030	597	689	31,918
2031	543	626	28,726
2032	489	564	25,535
2033	434	501	22,343
2034	380	439	19,151
2035	326	376	15,959
2036	272	313	12,767
2037	217	251	9575
2038	163	188	6384
2039	109	125	3192
2040	54	63	0

4.2. Number of Vehicles per Province in 2040

South Africa has nine constitutional provinces: Mpumalanga; Limpopo; Gauteng; North West; Northern Cape; Free State; KwaZulu Natal; Eastern Cape; and, Western Cape. The number of electric vehicles was calculated per province based on the World Reference scenario and the GDP scenario through the substitution of internal combustion vehicles (ICEVs) with their electric counterparts.

Figure 8 shows the number of electric cars per province for each scenario in year 2040.

For road passenger transport, GDP growth has been linked to an increased need to commute and greater personal wealth, which meant more money being available for vehicle purchases, in turn resulting in a demand for transport and transport fuel. Statistics South Africa [33] indicates that Gauteng contributed the highest (34.95% of the overall GDP) in 2016, while the lowest contribution was 2.19% from the Northern Cape Province. This correlates well with the results obtained. In 2040, Gauteng is expected to have the highest eCars (829,791 for the WR scenario and 110,809 for the GDP scenario), followed by KwaZulu Natal (380,790 for the WR scenario and 50,841 for the GDP scenario) and the Western Cape Province (329,574 for the WR scenario and 44,011 for the GDP scenario). The Northern Cape Province has the lowest, with 52,579 for the WR scenario and 7,021 for the GDP scenario.

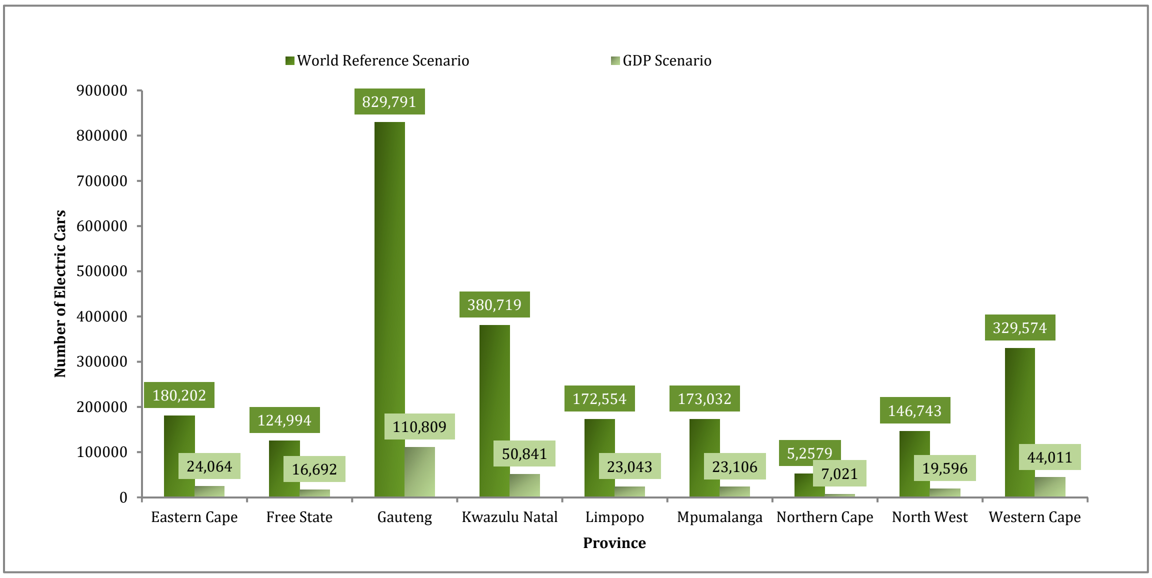


Figure 8. Number of eCars in 2040.

Figure 9 shows the number of electric trucks per province for each scenario in year 2040. Trucks facilitate economic opportunities that are related to the movement of people and goods and their impact on the environment would have to be well understood, since carbon emissions may moderate the otherwise favourable contribution of truck transport to socio-economic growth. Economic activity is dominated by almost all industries in Gauteng (13,752 eTrucks for the WR scenario and 2,431 for the GDP scenario), except for agriculture, forestry, and the fishing industry, which is dominant in KwaZulu Natal (4,832 eTrucks for the WR scenario and 854 for the GDP scenario) [34]. The large mining and quarrying distribution in economic activity could account for the large concentration of trucks in the Mpumalanga province (4,460 eTrucks for the WR scenario and 789 for the GDP scenario).

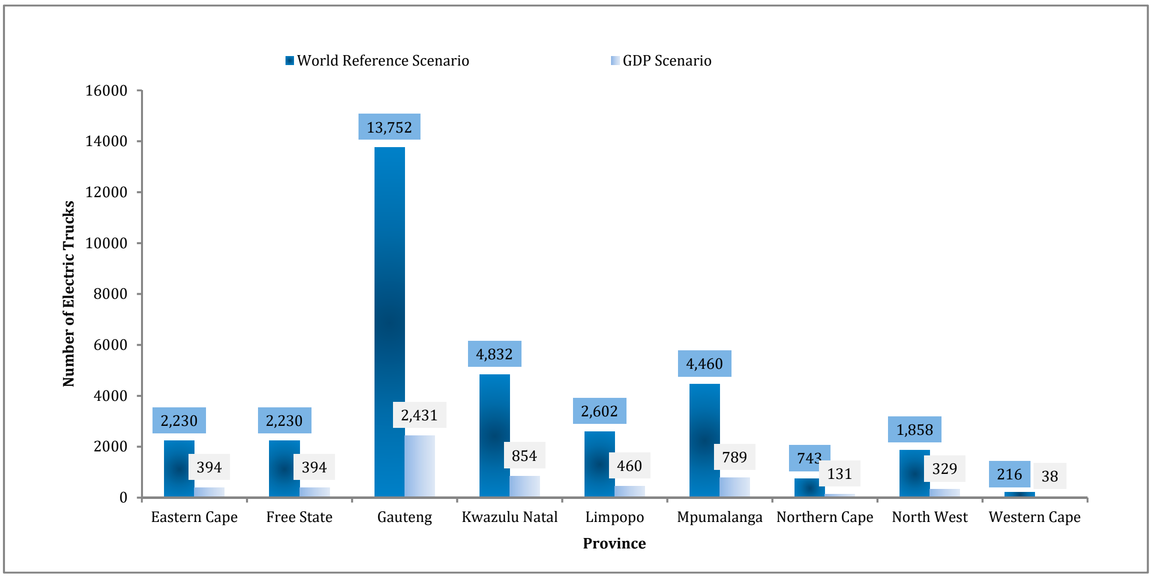


Figure 9. Number of eTrucks in 2040.

Figure 10 shows the number of electric buses per province for each scenario in year 2040. The South Africa government strongly subsidizes provincial bus services (R167bn towards infrastructure and operations), with plans to better integrate infrastructure to allow for corridors to be developed between rural and urban areas [35,36]. Figure 10 show the profile of eBuses with the highest number in Gauteng (16,352 for the WR scenario and 2,426 for the GDP scenario), followed by the KwaZulu Natal and Mpumalanga provinces (6,643 for the WR scenario and 985 for the GDP scenario).

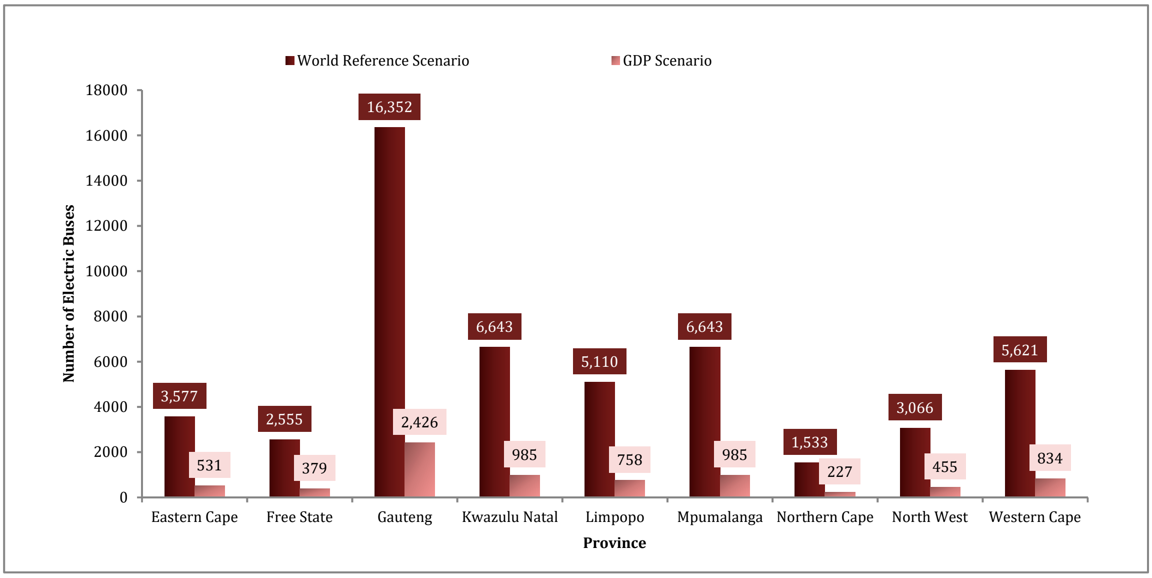


Figure 10. Number of eBuses in 2040.

Table 3 shows the national number of electric vehicles in 2040 for the two scenarios. If the economic structure of the country is taken into account, it appears that only 13.35% of Government's electric car target will be met in 2040. Using global targets for eBuses, South Africa still falls short of international trends with 51,100 eBuses in 2040, compared to China's forecasts of 1.3 million [31] by 2025. Using GDP as a measure of the national affordability of eBuses, this value is even lower at 7,850 eBuses in 2040. If 19% of the SA truck fleet were to electrify by 2040, there is an expectation for 70,709 eTrucks, and only 9.29% of this target may be achievable if the economic sector performance is used as an indicator.

Table 3. National Number of Electric Vehicles in 2040.

Scenario	eCars	eTrucks	eBuses
World Reference Scenario	2,390,189	70,709	51,100
GDP Scenario	319,182	6571	7580

4.3. Environmental Impact

Figure 11 shows the change in percentage of carbon emissions in the transport and electricity sectors from the base scenario with no electric vehicles, for both scenarios. For the World Reference scenario, the carbon emissions in the transport sector significantly decreases by 12.33%, while it increases in the electricity sector by 4.32% due to the coal fired base load power generation in SA, which means an overall decrease of 8% in national environmental carbon emissions. For the GDP scenario, the net impact is much smaller when the carbon emissions reduction in the transport sector is added to the increase in carbon emissions in the electricity sector, with a total net decrease of 1.13% in carbon emissions in the environment. The introduction of electrified vehicles outweighs the negative impact of using coal fired base load power generation to charge the vehicles in terms of carbon emissions for both of the scenarios.

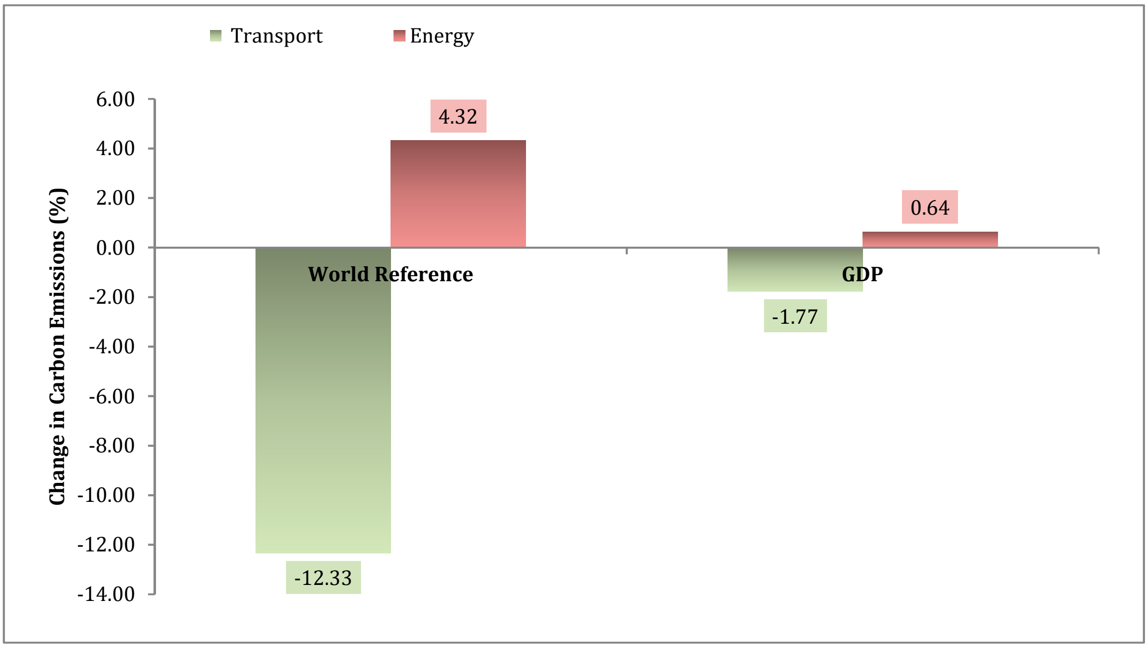
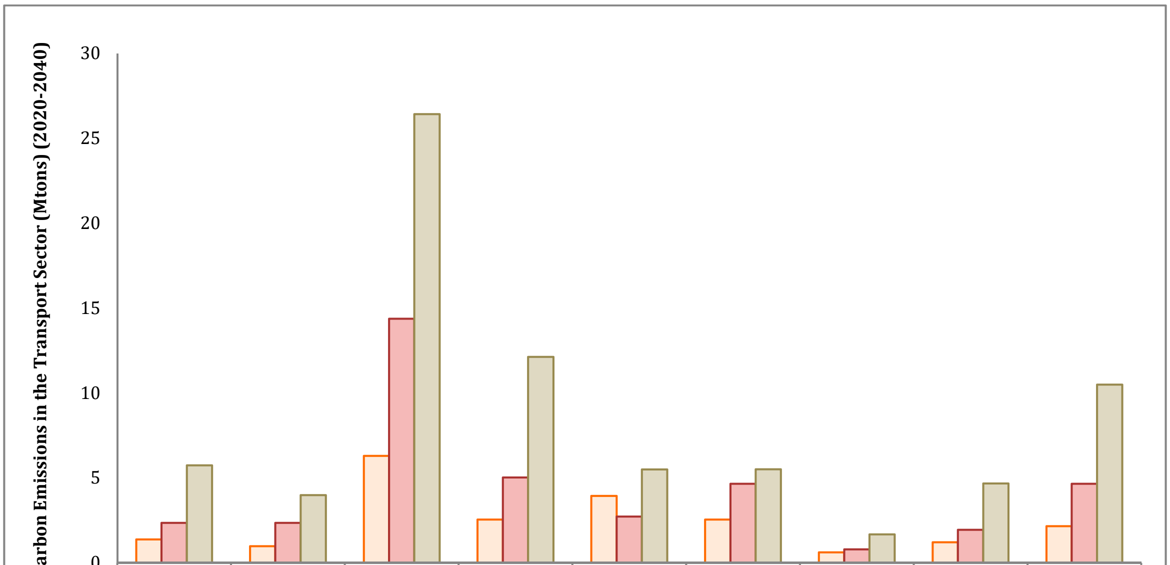


Figure 11. Carbon Emissions in the Transport Sector in 2040.

Calculations were conducted to determine the impact of electrified vehicles substituting combustion vehicles, based on the premise that the current South African generation mix will continue to use coal-fired power stations for baseload electricity generation (and to charge electric vehicles). Figure 12 shows the total carbon emission reduction due to 80% eBuses, 19% eTrucks, and 22% eCars. For all categories of electric vehicles, Gauteng province will experience the largest decrease in carbon emissions in the transport sector, followed by KwaZulu Natal and then the Western Cape province.

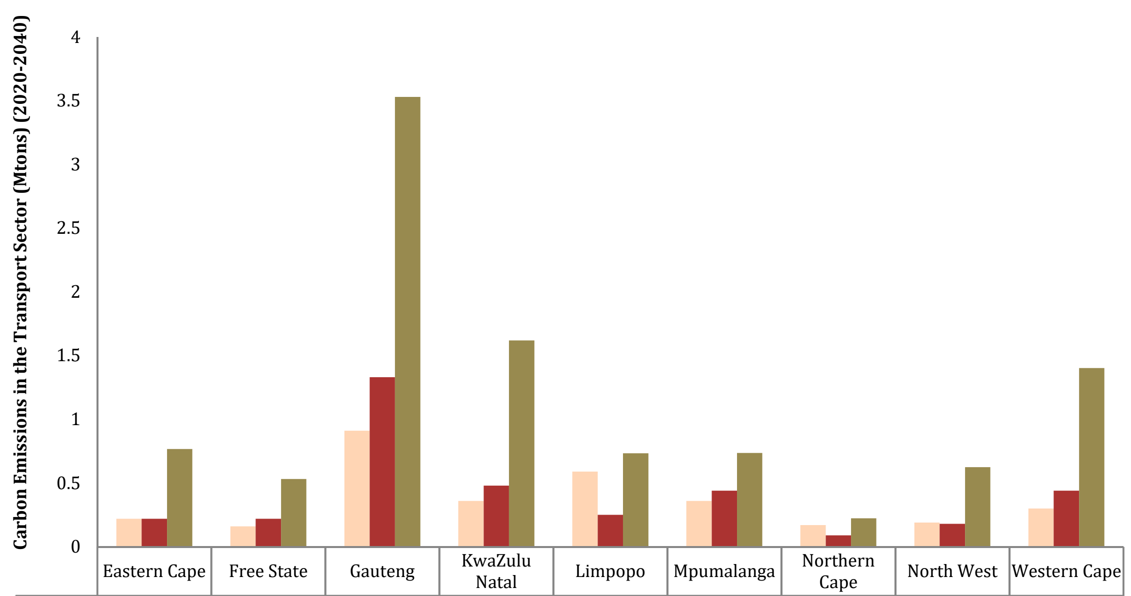


	Eastern Cape	Free State	Gauteng	KwaZulu Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape
Buses	1.38	0.98	6.3	2.55	3.94	2.55	0.61	1.21	2.16
Trucks	2.35	2.35	14.37	5.02	2.72	4.65	0.79	1.94	4.65
Cars	6	4	26	12	5	6	2	5	10

Figure 12. Total Carbon Emissions in the Transport Sector World Reference Scenario.

Road transport carbon emissions and the number of vehicles in each category would be related to the localised drivers within each province e.g. population, GDP, income distribution and affordability, economic sector activity, level of urbanisation, etc. The World Reference scenario assumes high volumes of electrified vehicles replacing their ICEV counterparts; however, achieving these targets would require overcoming several barriers. In the case of electric cars, purchase price parity, charging infrastructure, and range linked to battery capacity are significant challenges that would have to be overcome to meet the 2050 target of three-million set by the South African Department of Transport. Adopting a high number of eBuses would also involve overcoming several technological, financial, and institutional challenges [35]. Barriers to achieving eTruck adoption include factors such as weather impacts, commercial charging infrastructure, high battery costs, etc. [37]

Figure 13 shows the total carbon emission reduction in the transport sector due to 12% eBuses, 1.79 % eTrucks and 2.382% eCars in the GDP scenario. The highest decrease in carbon emissions would be in Gauteng for eCars (3.529 Mtons), eBuses (0.91 Mtons), and eTrucks (1.33 Mtons). The least the impact on decreasing carbon emissions in the transport sector for eBuses would be for the Free State (0.16 Mtons). The Northern Cape shows the least impact on carbon emissions for eCars (0.224 Mtons) and for the eTrucks (0.09 Mton).



	Eastern Cape	Free State	Gauteng	KwaZulu Natal	Limpopo	Mpumalanga	Northern Cape	North West	Western Cape
Buses	0.22	0.16	0.91	0.36	0.59	0.36	0.17	0.19	0.3
Trucks	0.22	0.22	1.33	0.48	0.25	0.44	0.09	0.18	0.44
Cars	0.766	0.532	3.529	1.619	0.734	0.736	0.224	0.624	1.401

Figure 13. Total Carbon Emissions in the Transport Sector GDP Scenario.

5. Conclusions

It was established that a system dynamics modelling approach incorporating feedback loops allowed for non-linear mathematical causal linkages of a wide spectrum of variables after reviewing various modelling methods that have been used to understand EV dynamics, which supported an in-depth understanding of the impact of the market penetration rate of EVs on carbon emissions. The method was particularly of use for exploratory modelling and descriptive comparative scenario analysis, as opposed to predictive system behaviour, down to the last decimal place.

For the World Reference scenario, Gauteng has the highest (829,791) number of eCars in 2040, followed by KwaZulu Natal (380,719) and the Western Cape Province (329,574). If GDP is used as a correction to the economic structure and affordability of electric vehicles, then Gauteng would have 110,809 eCars, KwaZulu Natal would have 50,841, and the Western Cape would have 44,011 eCars.

For the World Reference scenario, Gauteng province is also expected to have the highest number of eTrucks (13,752), followed by KwaZulu Natal (4,832) and the Mpumalanga (4,460) province. The GDP scenario results in 2,431 eTrucks for Gauteng, 854 for KwaZulu Natal, and 789 for the Mpumalanga province. The Western Cape province will experience the lowest eTruck market penetration (38 for the GDP scenario and 216 for the World Reference scenario). Gauteng, KwaZulu Natal, and the Mpumalanga provinces also dominate the eBus market penetration for both the World Reference scenario and the GDP scenario.

The World Reference scenario results in a 12.33% decrease in net carbon emissions, while the GDP scenario results in a 1.13% decrease. For both scenarios, the introduction of electrified vehicles outweighs the negative impact of using coal fired base load power generation to charge the vehicles in terms of carbon emissions.

The greatest decrease in environmental carbon emissions for all vehicle categories occurs for the World Reference scenario. It is also important to note that although the eCar market penetration yields positive results in terms of reducing carbon emissions, the volumes required is large (2.9 million eCars by 2040) and various other factors, such as affordability in the various income deciles, would have to be considered in determining whether this volume is achievable in South Africa. Studies by Pillay et.al [4] indicate that expected eCar targets could be less by as much as 80% if price parity for vehicles is not achieved and if disposable income and affordability are used as measures to determine the number of vehicles that may be purchased by the income groups in South Africa. The South African Department of Trade and Industry would have to negotiate lower import taxes on EVs with the European Union from 25% to achieve the high volumes of eCars [38], in an effort to reduce the retail prices of electric vehicles; in tandem with international efforts to reduce overall battery production costs.

Although eBuses could reduce carbon emissions in the transport sector, charging would have to be through renewable electricity sources, to compete with the advantages expected from other projects such as the Metrobus Going Green initiative [36], which are underway to reduce emissions by converting diesel buses to diesel dual fuel.

Further research could include the impact of electrifying minibus taxi's on carbon emissions, since the lower income groups are dependent on this form of transport, with the fraction of minibus taxi's being about 20% of the vehicle population in 2016 [38,39].

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References

1. Lehr, R. New Utility Business Models: Utility and Regulatory Models for the Modern Era. *Electr. J.* **2013**, *26*, 35–53. [CrossRef]
2. Bekker, B.; Eberhard, A.; Gaunt, T.; Marquard, A. South Africa's rapid electrification programme: Policy, institutional, planning, financing and technical innovations. *Energy Policy* **2008**, *36*, 3125–3137. [CrossRef]
3. Tayal, D. Disruptive forces on the electricity industry: A changing landscape for utilities. *Electr. J.* **2016**, *29*, 13–17. [CrossRef]
4. Sooknanan Pillay, N.; Brent, A.C.; Musango, J.K. Affordability of Battery Electric Vehicles based on Disposable Income and the Impact on Provincial Residential Electricity Requirements in South Africa. *Energy J.* **2018**, *171*, 1077–1087. [CrossRef]
5. Ervural, B.C.; Evren, R.; Delen, D. A multi-objective decision-making approach for sustainable energy investment planning. *Renew. Energy* **2018**, *126*, 387–402. [CrossRef]

6. Krishnan, V.; Ho, J.; Hobbs, B.F.; Liu, A.L.; McCalley, J.D.; Shahidehpour, M.; Zheng, Q. Co-optimization of electricity transmission and generation resources for planning and policy analysis: Review of concepts and modeling approaches. *Energy Syst.* **2016**, *7*, 297–332. [CrossRef]
7. Dyner, I.; Larsen, E.R. From planning to strategy in the electricity industry. *Energy Policy* **2001**, *29*, 1145–1154. [CrossRef]
8. Foley, A.M.; OGallachoir, B.P.; Hur, J.; Baldick, R.; McKeogh, E.J. A strategic review of electricity systems models. *Energy* **2001**, *35*, 4522–4530. [CrossRef]
9. Al-Alawi, B.; Bradley, T. Review of Hybrid, Plug-In Hybrid, and Electric Vehicle Market Modeling Studies. *Renew. Sustain. Energy Rev.* **2013**, *21*, 190–203. [CrossRef]
10. Grahn, P. Electric Vehicle Charging Modeling. Ph.D. Thesis, School of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden, 2014.
11. Nemry, F.; Brons, M. Market penetration scenarios of electric drive vehicles. In *Plug-in Hybrid and Battery Electric Vehicles*; Publications Office of the European Union: Luxembourg, 2010.
12. Stadler, M.; Marnay, C.; Sharma, R.; Mendes, G.; Kloess, M. Modeling Electric Vehicle Benefits Connected to Smart Grids. In Proceedings of the 7th IEEE Vehicle Power and Propulsion Conference, Chicago, IL, USA, 6–9 September 2011.
13. Sterman, J.D. *Business Dynamics: Systems Thinking and Modelling for a Complex World*; McGraw-Hill: New York, NY, USA, 2000.
14. DOT. Green Transport Strategy. Available online: http://www.transport.gov.za/documents/11623/89294/Green_Transport_Strategy_2018_2050_onlineversion.pdf/71e19f1d-259e-4c55-9b27-30db418f105a (accessed on 2 April 2019).
15. Pillay, N.S.; Brent, A.C.; Musango, J.K.; Van Geems, F.; Tyob, K. Planning for eMobility in an Electricity Utility. In Proceedings of the Research Conference, Johannesburg, South Africa, 11 September 2018.
16. Andersen, D.F.; Richardson, G.R. Scripts for Group Model Building. *Syst. Dyn. Rev.* **1997**, *13*, 107–129. [CrossRef]
17. Environmental Defence Fund. The Way Forward 2014 Annual Report. Available online: https://www.edf.org/sites/default/files/AR2014/EDF_AR2014.pdf (accessed on 10 April 2019).
18. Richardson, G.P.; Pugh, A.L., III. *Introduction to System Dynamics Modelling*; Pegasus: Franklin, MA, USA, 1989.
19. Pillay, N.S. System Dynamics Simulation of Income Distribution and Electric Vehicle Diffusion for Electricity Planning in South Africa. Ph.D. Thesis, University of Stellenbosch, Stellenbosch, South Africa, 2018.
20. Gentner, D. *Mental Models, Psychology of*; Smelser, N., Baltes, P., Eds.; Elsevier: Chicago, IL, USA, 2001.
21. Vennix, J.A. Group Model Building: Tackling Messy Problems. *Syst. Dyn. Rev.* **2000**, *15*, 379–401. [CrossRef]
22. iSee System Products; iSee Systems. Available online: http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx (accessed on 14 January 2017).
23. Qudrat-Ullah, H. Structural validation of System Dynamics and Agent-based Simulation Models. In Proceedings of the 19th European Conference on Modelling and Simulation, Riga, Latvia, 1–4 June 2005.
24. Sargent, R.J. Verification and validation of simulation models. *J. Simul.* **2013**, *7*, 12–24. [CrossRef]
25. DOE. Integrated Energy Plan (IEP). Department of Energy. Available online: http://www.energy.gov.za/files/IEP/presentations/Integrated-Energy-Plan-22-Nov-2016.pdf. (accessed on 19 January 2018).
26. DEA. GHG National Inventory Report South Africa 2000–2012. 2016. Available online: https://cer.org.za/wp-content/uploads/2014/02/Draft-GHG-Inventory-Report-SA.pdf (accessed on 4 April 2019).
27. Langley, P. *Electric Vehicles Research Results 2014*; Eskom SOC: Johannesburg, South Africa, 2015.
28. Meyer, P. Bi-Logistic Growth. *Technol. Forecast. Soc. Chang.* **1994**, *47*, 89–102. [CrossRef]
29. Eskom SOC. Eskom's Integrated Report. Eskom. Available online: http://www.eskom.co.za/IR2017/Documents/Eskom_integrated_report_2017.pdf (accessed on 12 April 2018).
30. BNEF. Electric Buses Market will Grow Faster than Electric Cars, According to Bnef. 2018. Available online: https://www.sustainable-bus.com/news/bloomberg-new-energy-finance-long-term-forecast-on-electric-buses-vehicles/ (accessed on 8 April 2019).
31. BNEF. Electric Vehicle Outlook 2019. Available online: https://www.eenews.net/assets/2019/05/15/document_ew_02.pdf (accessed on 19 November 2019).
32. Reyneke, M.; Sorokáčová; A; Pitt, L. Managing brands in times of economic downturn: How do luxury brands fare? *J. Brand Manag.* **2012**, *19*, 457–466. [CrossRef]

33. Statistics, S.A. Gross Domestic Product 4th Quarter 2017. Available online: http://www.statssa.gov.za/publications/P0441/GDP_Q4_2017_Media_presentation.pdf (accessed on 3 April 2019).
34. StatsSA. Regional Estimates. Available online: http://www.statssa.gov.za/economic_growth/16%20Regional%20estimates.pdf (accessed on 12 April 2019).
35. Sclar, R.; Gorguinpour, C.; Castellanos, S.; Li, X. Barriers to Adopting Eletric Buses. Available online: https://wrirosscities.org/sites/default/files/barriers-to-adopting-electric-buses.pdf (accessed on 20 November 2019).
36. Metrobus. Metrobus Going Green for the Environment Diesel Dual Fuel(DDF) Buses as a Strategic Project CNG Conversions Project. Available online: http://www.mbus.co.za/index.php/testimonials-87 (accessed on 4 April 2019).
37. Brotherton, T.; Gilde, A.; Tomic, J. Key Barriers Affecting E-Truck Adoption, Industry and Policy Implications, and Recommendations to Move the Market Forward. *World Electr. Veh. J.* **2016**, *8*, WEVJ8-0657.
38. Omarjee, L. Public Transport Can Drive Economic Growth. Available online: https://www.fin24.com/Economy/public-transport-can-drive-economic-growth-20160704 (accessed on 12 April 2019).
39. eNatis. Road Traffic Report. 2018, pp. 10–11. Available online: eNatis.com (accessed on 10 October 2016).