INSIGHTS INTO ELECTRIC VEHICLE MARKET GROWTH IN SOUTH AFRICA: A SYSTEM DYNAMICS APPROACH

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ABSTRACT

The international share of plug-in electric vehicle sales was 8.6% in 2021, compared with South Africa's 0.1%. Increasing the sale of these vehicles in South Africa is directly tied to the continued existence of South Africa's vehicle manufacturing industry. To address this challenge, businesses and governments need to understand better the factors influencing electric vehicle adoption. This study identified significant factors that influence and are influenced by electric vehicle adoption. By reviewing the current literature, numerous factors were identified and mapped in a causal loop diagram with an adapted system dynamics approach. The impact of taxation on the cost of electric vehicles and the low availability of electricity negatively affects both consumer confidence in owning an electric vehicle and local manufacturing capacity. This model serves as a useful tool to piece together how various factors in South Africa affect and are affected by electric vehicle adoption.

OPSOMMING

Die internasionale aandeel van elektriese voertuie wat van die kragnetwerk af herlaai word se verkope was 8,6% in 2021, in vergelyking met Suid-Afrika se 0,1%. Die verhoging van die verkoop van hierdie voertuie in Suid-Afrika is direk gekoppel aan die voortbestaan van Suid-Afrika se voertuigvervaardigingsbedryf. Om hierdie uitdaging die hoof te bied, moet besighede en regerings die faktore wat die aanvaarding van elektriese voertuie beïnvloed, beter verstaan. Hierdie studie het beduidende faktore geïdentifiseer wat die aanvaarding van elektriese voertuie beïnvloed en daardeur beïnvloed word. Deur middel van 'n literatuurstudie, is talle faktore geïdentifiseer en daarna gekarteer in 'n kousale lusdiagram met 'n aangepaste sisteemdinamika-benadering. Die impak van belasting op die koste van elektriese voertuie en die lae beskikbaarheid van elektrisiteit beïnvloed beide verbruikersvertroue in die besit van 'n elektriese voertuig en plaaslike vervaardigingskapasiteit negatief. Hierdie model dien as 'n nuttige hulpmiddel om te verstaan hoe verskeie faktore in Suid-Afrika die aanvaarding van elektriese voertuie beïnvloed en daardeur beïnvloed word.

1. INTRODUCTION

A paradigm shift is taking place worldwide. The rapid development of electric vehicles (EVs) is signalling the end of the internal combustion engine vehicle (ICEV) era. EVs accounted for 14% of all vehicles sold internationally in 2022, compared with the minuscule 0.17% in South Africa during the same period [1]. The move towards electrification is accelerated by the imminent ban on ICEV sales in various markets [2]. This ban is primarily motivated by environmental concerns. While a ban on ICEVs is not being planned for South Africa, continuing production of ICEVs for a reducing market is an unviable business model. Therefore, local EV adoption must be increased to use the benefits of the economy of scale (ES) in local manufacturing. and to enable South Africans to benefit from international transportation trends.

1.1. South African challenges

At first glance, the low adoption rate of EVs in South Africa seems puzzling, as various factors influence it. Some of the most obvious are the large geographic area of South Africa, the low number of public fast chargers, and the high cost of electric vehicles. The current average EV range of 350 km may not be enough to address the range anxiety of consumers who frequently travel distances that exceed 200 km daily [3]. Another limitation is the low number of fast chargers specifically on the extensive road network. Furthermore, many of the fast chargers are relatively low in power (around 60 to 80 kW) compared with the charging power capacity (>270 kW) of modern EVs [4], [5], which can further contribute to range anxiety [6]. The high cost of EVs, especially compared with ICEVs, puts them out of the reach of most South Africans. South Africa is also the only country in the world where the tax on imported EVs exceeds the tax on imported ICEVs [7]: imported EVs are taxed at 7% more than the rate for ICEVs [8], [9] which is contrary to the international norm of reducing the taxes paid on EV purchases to accelerate their adoption.

The long distances, inadequate infrastructure, and high cost of EV purchasing make it a problematic sales proposition – even for the most ardent supporter of this next generation of transportation technology. These constraints are small pieces in the puzzling array of factors influencing EV adoption.

1.2. Problem identification

South Africa relies heavily on export markets to sustain local production. Of the 351,785 vehicles manufactured locally in 2022, 36.8% were exported [10] with a value of R227.6 billion. These exports accounted for 12.4% of the value of all exports from South Africa. However, most of these exports were to countries planning to ban ICEVs by the 2030s [10]. Therefore, a transition to local EV production needs to be made to maintain these high-value export markets.

The economies of scale and low production costs are some of the characteristics that enable the high vehicle production volumes in South Africa. Although it would be possible to export the majority of EVs that could be produced locally, the preference would be to have strong local demand as well. Manufacturers have few reasons to remain in the difficult South African manufacturing space without strong local demand. If these manufacturers were to leave, the local vehicle manufacturing industry would likely collapse [11], affecting more than 116,000 formal jobs and reducing the value of the South African economy by 4.9% [10]. Therefore, it is crucial to stimulate the local sales of EVs to incentivise local EV production.

There are numerous factors that, directly and indirectly, impact consumers' willingness to consider an EV. However, various stakeholders in the supply chain of EVs are uncertain about how these factors could be leveraged to improve EV adoption. In addition, this uncertainty affects entrepreneurs and policymakers who recognise the potential to create value from the EV transition. Therefore, piecing together how these factors influence EV adoption is critical to establishing a sustainable market for EVs in South Africa. This knowledge would assist entrepreneurs and policymakers in developing long-term business strategies, creating value-adding products and services, and matching demand with sufficient deliverable capacity to ensure maximum revenue. This study's objective is to determine the key factors affecting EV adoption and their causal relationships, using an adapted systems dynamics approach. The factors and their relationships are presented in a qualitative model. A causal loop diagram (CLD) is used to visualise the qualitative model. CLDs are well suited to illustrating the positive or negative relationships between factors. The CLD in this study is not developed into a simulation model, as the main priority of this study is to identify the factors and their relationships. As a result, a scenario analysis of changes to the system is not included. Nevertheless, the CLD is analysed visually with the aid of the literature study's findings, to identify key factors and relationships that strongly influence the modelled system.

2. LITERATURE REVIEW

The South African literature on EV adoption is relatively limited [12]. Therefore, this study has relied on international studies from South Africa [12], India [13], the USA [14], [15], China [16], Germany [17], and Korea [18]. These studies, and others, were used to identify the factors that influence EV adoption, forming the basis of the model developed in this study.

Previous studies focus mainly on the factors that are directly perceived by the consumer. However, various other factors indirectly influence the consumer by affecting those that the consumer directly perceives. Examples are vehicle manufacturing's contribution to consumer income, the cost of vehicles, and South

Africa's gross domestic product (GDP) [10]. Thus it is vital to include the vehicle and part manufacturers' influence as a group of factors within the broader vehicle category.

Kim *et al.* [18] identified five main categories into which the factors influencing EV adoption can be grouped. These categories are: automobile (vehicle) characteristics, costs, charging conditions, policies, and perceptions. These five categories are discussed in the sections that follow.

2.1. Automobile characteristics

One main component differentiating EVs from ICEVs is their electric drivetrains. Consumers can appreciate the drivetrains, yet they can also negatively impact consumers' perception of the product. In particular, the limited driving range currently available is considered one of the most significant shortcomings of EVs, leading to range anxiety among potential buyers [13], [14].

Despite their limited range, EVs offer a significant advantage over ICEVs. Owners can recharge their vehicle's battery at any household power connection, eliminating the need for centralised energy distribution points such as fuel stations [19]. This advantage reduces the reliance on public charging infrastructure, making EVs more attractive to potential buyers.

2.2. Costs

The cost disparity between EVs and similarly classed ICEVs remains one of the greatest shortcomings of the former. EVs are particularly expensive because of their battery-powered drivetrains, which are complex to produce and require significant investment in research and development. However, the increased global production rates of EVs have decreased their manufacturing costs, with the help of ES. The local production of EVs could contribute substantially to the local economy [20]. In addition, local production could lower the cost of purchasing and owning an EV further by reducing import costs and tariffs.

The high cost of EVs compared with ICEVs is a major obstacle to their adoption, as it requires a significant initial investment from consumers. Although the low running costs of EVs are considered an important motivator for their adoption, the high purchase price remains a deterrent [13], [14], [17]. The high adoption rate of EVs in Norway can be directly attributed to their world-leading tax incentives that lower EVs' costs [21].

The mechanical simplicity of EVs results in significantly lower maintenance costs compared with ICEVs [22]. Moreover, EVs are known for their energy efficiency, resulting in lower energy costs because of the low cost of electricity per kWh compared with petrol, and because of their high energy efficiency [23]. The lower operating cost offers a positive incentive for consumers to consider purchasing an EV.

2.3. Charging conditions

While some EV owners use private residential chargers, a large portion of potential EV owners would require a public charging infrastructure to recharge their EVs owing to a lack of access to private residential chargers. EV adoption has been positively correlated with the density of a public charging infrastructure [18], [24]. An increase in the number of chargers would also increase the visibility of the charging infrastructure, promoting the viability of EVs.

However, the total number and density of chargers available to consumers are only a part of how chargers influence EV adoption. The low number of fast chargers has been identified as one of the main reasons for range anxiety [6]. Therefore, increasing the overall number and density of fast chargers would reduce range anxiety and increase consumers' 'usable' range [13], [25]. As a result, increasing the number of slow and fast chargers would be one of the most effective strategies that governments and businesses could employ to increase consumer willingness to consider an EV.

2.4. Policy

Governments and businesses primarily use incentives as a policy tool to improve the adoption rate of EVs. These incentives could take the form of direct subsidies, such as government subsidies on purchase prices or reductions in periodic vehicle taxes. Alternatively, they could be indirect, such as reduced electricity prices and increased fuel costs [6].

Direct financial incentives can be classified as either circulation or registration-type subsidies [24]. A study on the influence of total incentives on EV adoption found that countries with high incentive rates tended to have higher EV market shares, while countries with low incentive rates had lower market shares [24].

However, all policies have associated economic, social, or operational costs. Therefore, it is vital to limit inefficient policies, especially those that might harm other aspects of society [21]. It is also important to limit the total cost of subsidies by gradually decreasing and eventually withdrawing them as the market becomes more self-sufficient over time [21]. While the withdrawal of specific policies may not directly influence EV adoption, the negative impacts that could arise from an ill-timed policy withdrawal could have long-term effects on EV adoption.

2.5. Consumer characteristics

Peer influence can impact purchasing behaviours. Ownership of EVs by family, friends, or acquaintances increases the likelihood of individual consumer adoption [21]. Moreover, it was found that urban EV owners can have a persuasive effect on the adoption decisions of other consumers.

Another characteristic that impacts the likelihood of EV adoption is disposable income. There is a positive correlation between a household's disposable income and the probability of purchasing an EV [26]. In addition, education level plays a role in influencing consumer behaviour. EVs are commonly perceived as advanced technology products, making them particularly appealing to educated consumers. Early adopters of EVs often have higher levels of education [14]. However, educated consumers are also more aware of the problems associated with EVs, such as cost, charging time, and battery range limitations [14].

3. METHODOLOGY

To model the functionality of the EV market and its supply chains, an iterative modelling process such as system dynamics (SD) is required. SD is a modelling methodology that is well-suited for large-scale socio-economic-environmental system analysis with a high degree of complexity [27]. It uses feedback control theory to understand the behaviour of complex systems over a specific period, and its feedback loops are easily visualised in CLDs [27], [28]. SD is preferred for modelling the EV market because of its inherent structural ability to visualise and explain the relationships between the various factors. Consequently, CLDs enable the visualisation of the factors' reinforcing and conflicting effects on the adoption rate over time. The SD modelling process is thus a valuable tool for understanding and modelling the complex system of the EV market. By identifying the key factors and establishing their causal relationships, policymakers and stakeholders could make informed decisions about policies that would promote the adoption of EVs.

This study uses an adapted version of the SD modelling method of Sterman [29]. This method was chosen because the problem is strategic in nature and is at a high level of abstraction. The full method involves an iterative approach, moving back and forth between hypothesis formulation, testing, and revision. The steps in the full method are as follows:

1. Problem articulation (boundary selection) and selection of the time horizon.
2. Formulation of a dynamics hypothesis that describes the problematic behaviour and explains the system's dynamics.
3. Formulation of a simulation model.
4. Testing to compare the model to determine whether it accurately reproduces the problematic behaviour.
5. Policy design and evaluation.

This study uses the first two steps of the modelling process to develop the qualitative model needed to address this problem. Therefore, no simulation model is developed, tested, or analysed in this study.

3.1. Setting model boundaries

Identifying and including only relevant factors within the model's boundaries is essential while continually evaluating and adjusting them to develop a manageable model. The factors that are not included in the model are discussed first. EVs' carbon mitigation aspect is considered unimportant to South African consumers [12]. Therefore, the impact of EVs on carbon dioxide emissions in South Africa are not included. The market dynamics of ICEVs will not be included either, to narrow the focus on the EV problem. Second-hand EV sales will also not be included, as fewer than 2,500 EVs are currently on South African roads [1]. Finally, the fossil fuel market is excluded, as many of the market dynamics in this system are exogenous to the South African market. The omission of these factors, which could lead to increased inaccuracy for the bounded scope if the model were to be simulated, reduces its complexity. However, the purpose of this study is to model visually the controllable influential factors. Therefore, the omission of these factors does not have a negative impact, as no simulation is required.

4. MODELLING

To develop an effective model, it should specifically address the main problem of the study and identify the influential factors that can be represented in a qualitative framework [29]. This study involves two distinct steps: setting model boundaries and developing a dynamic hypothesis. Continuous iteration occurs between these two steps to refine and improve the model. The main deliverable is a CLD that can provide valuable insights into the problem and help to inform potential solutions.

4.1. Setting model boundaries

Identifying and including only relevant factors within the model's boundaries is essential while continually evaluating and adjusting them to develop a manageable model. The factors that are not included in the model are set out in the boundary setting step. EVs' carbon mitigation aspect is considered unimportant to South African consumers [12]. Therefore, the impact of EVs on carbon dioxide emissions in South Africa is not included. The market dynamics of ICEVs are not included either to narrow the focus on the EV problem. Second-hand EV sales are also not included, as fewer than 2,500 EVs are currently on South African roads [1]. Finally, the fossil fuel market is excluded, as many of the market dynamics in this system are exogenous to the South African market. The omission of these factors, which could lead to increased inaccuracy for the bounded scope if the model were to be simulated, reduces its complexity. However, the purpose of this study is to model visually the controllable influential factors. Therefore, the omission of these factors does not have a negative impact, as no simulation is required.

4.2. Identifying the main variables

Once the model's boundaries have been set, endogenous factors can be explicitly included. These factors were identified and grouped into the five categories discussed in the literature review: automobile characteristics, costs, charging conditions, policies, and perceptions.

4.2.1. Determining the time horizon and reference frame

With the initial system boundaries defined, the behavioural aspects of the system can be investigated. First, the impact of the passing of time is addressed when the time horizon is discussed. Then, perhaps more importantly, the system's behaviour can be understood by determining the reference frame.

The time horizon for this problem is not as vital as it would be for problems requiring simulation. However, the model is broadly developed to apply to the initial adoption of EVs from 2013 to 2035. To understand better how the problem being modelled functions, specific reference frames can provide a helpful starting point. The main frame of reference used in this model's development is how innovation diffuses in a society.

4.2.2. The diffusion of innovation

The diffusion of innovation follows a spreading behaviour. As more people adopt an innovative concept or product and are happy with the improvements it brings to their lives, they are willing to spread the reputation to the people with whom they have contact. Better innovations have higher degrees of 'virality' and diffuse into society more quickly. In addition, certain environmental factors can increase or decrease the diffusion rate. Many innovations follow an S-shaped adoption pattern, characterised by a slow initial adoption rate that increases as more people adopt it. Once most people have adopted the innovation, the rate slows down as the population that can adopt the idea decreases. In the case of a vehicle market, factors such as disposable income and vehicle cost play a significant role in determining the potential innovation population pool.

The diffusion of innovation is most frequently modelled with the logistic growth model. However, the Bass diffusion model was chosen to model EV diffusion. It addresses one of the flaws of logistic growth models, which is that they cannot explain the initial growth in innovation when the starting number of adopters is 0. The Bass model overcomes the start-up problem by assuming that consumers become aware of innovation through external sources whose magnitude and persuasiveness remain relatively constant over time [30]. A positive feedback loop, usually word of mouth, drives the increased adoption rate.

4.3. Dynamic hypothesis

The concept of a dynamic hypothesis is essential in explaining the problematic behaviour of a system, as it describes a constantly changing system that results from underlying feedback [29]. The hypothesis is dynamic because it explains the dynamics characterising the problem, and is subject to the feedback structure causal effects underlying the system. Developing a dynamic hypothesis is an iterative process that involves creating and revising a hypothesis rather than a final model/structure. This iterative process allows adjustments to be made to the model as more data and insights become available to the modeller. It is essential not to exclude specific explanations for causal structures that influence the problem during this process. These explanations should be tested for additions and improvements to the final hypothesis.

4.4. Developing the causal loop diagram

Various factors influencing EV adoption were identified during the initial boundary setting. The new endogenous factors that link the existing factors can often blur the distinctions between the five categories. Therefore, the five category modules are aggregated into three to explain better the underlying mechanisms that influence these variables.

The CLD of this model consists of one uniting overall structure, visualised in Figure 1, that uses three-factor modules. The first module is the vehicle module, which includes the factors related to the automobile characteristics category, the policies influencing vehicle ownership, and the costs associated with purchasing and maintaining an EV. The next module is the energy module, which includes factors related to EV chargers and electricity. Factors relating to policies that influence these factors and the prices of the factors are also included in this module. Finally, the consumer module contains the factors from the consumer characteristics. These three modules of factors influence the inclination of consumers to purchase an EV.

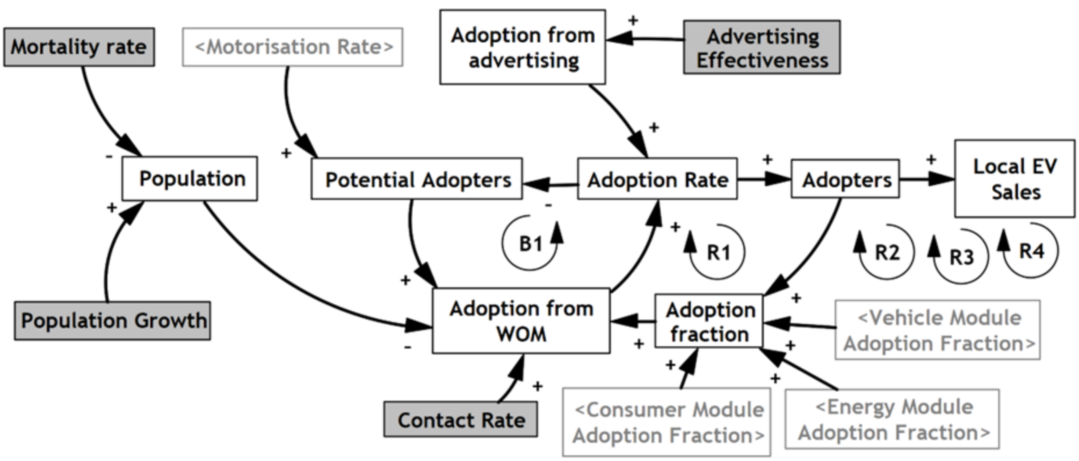

Figure 1: Causal loop diagram of overall model

The three-factor modules feed into the adoption fraction factor of the Bass model of diffusion. The Bass model of diffusion of innovation is adjusted to consider that the three different factor modules include the adoption fraction. Figure 1 also illustrates the adapted Bass model. As the number of adopters increases, its causal impact on the adoption rate increases. The three-factor modules result in three reinforcement loops (R2, R3, R4).

With the directly influential factors re-organised, new factors that help to describe the endogenous behaviour of the system can be added as needed. The causal relationships that describe the behaviour of these factors can also be established. A more realistic representation of the problematic system can then be shown with CLDs.

The general model includes, among other things, the growth rate of the population and the rate at which consumers can purchase a vehicle (the motorisation rate). These two factors influence the rate at which consumers become potential adopters of EVs. The causal effect of advertising on the adoption rate is also shown in this module.

A causal relationship found in all three modules is the effect of taxation on the cost of a product. If the tax rate increases, the cost is typically passed down to the consumer to avoid reducing a company's profit. The government receives an income from the taxes levied on producing and selling products. Furthermore, in all three modules, economic activities in South Africa, such as resource extraction and refining, manufacturing, and retail, contribute to the South African economy.

4.4.1. Vehicle

The development and construction of an EV are arguably some of the most important factors influencing the adoption of EVs. These factors affect the cost of producing the vehicle, its performance, and the cost of ownership. This module is illustrated in Figure 2.

As more vehicles are adopted and purchased, the cost of manufacturing the vehicles can be driven down through ES (B4). Spreading production costs and improved knowledge of EV manufacturing methods reduces EV manufacturing costs (B5). In addition, local vehicle production can reduce costs even further by removing import costs. However, these cost benefits can be quickly diminished if the current EV taxation structure is used to determine the final cost price.

Component manufacturing, and the resource extraction facilitating this production, increase the contribution of vehicle manufacturing to the local economy. This contribution is mainly in employment, taxation, and value-adding to resources. However, as no country can produce all of the resources and parts required to manufacture vehicles, imports match the pull for products downstream in the vehicle supply loop. This pull originates from consumer demand for EVs. As the number of EVs increases, vehicle and battery development demands are stimulated.

Vehicle and battery development are driven by companies who try to out-compete one another. The increased battery and vehicle development levels are the causal factors that lead to improved vehicles. Consumers value improved vehicle performance (R5). Vehicle development also enables improved vehicle efficiency. The enhanced efficiency and improved battery energy density lead to increased vehicle range (R6, R7). Improved efficiency likewise leads to reduced operational costs of driving an EV if the unit cost of electricity is constant. Reducing operating costs is another advantage that motivates consumers to purchase an EV (R8). Conversely, any increase in operational cost, perhaps owing to potentially high registration taxes, decreases the attractiveness of EVs to consumers.

It is essential to note the influence of continued loadshedding on the output of South Africa's factories. Factories either reduce their production during loadshedding to lower the number of generators required to maintain normal electricity supply levels, or stop production altogether. Consequently, loadshedding leads to missed opportunities to collect taxes and reduces the impact of local value creation. The demand for electricity for both the manufacturing and use of EVs significantly strains the South African electrical grid, and is discussed in the next module.

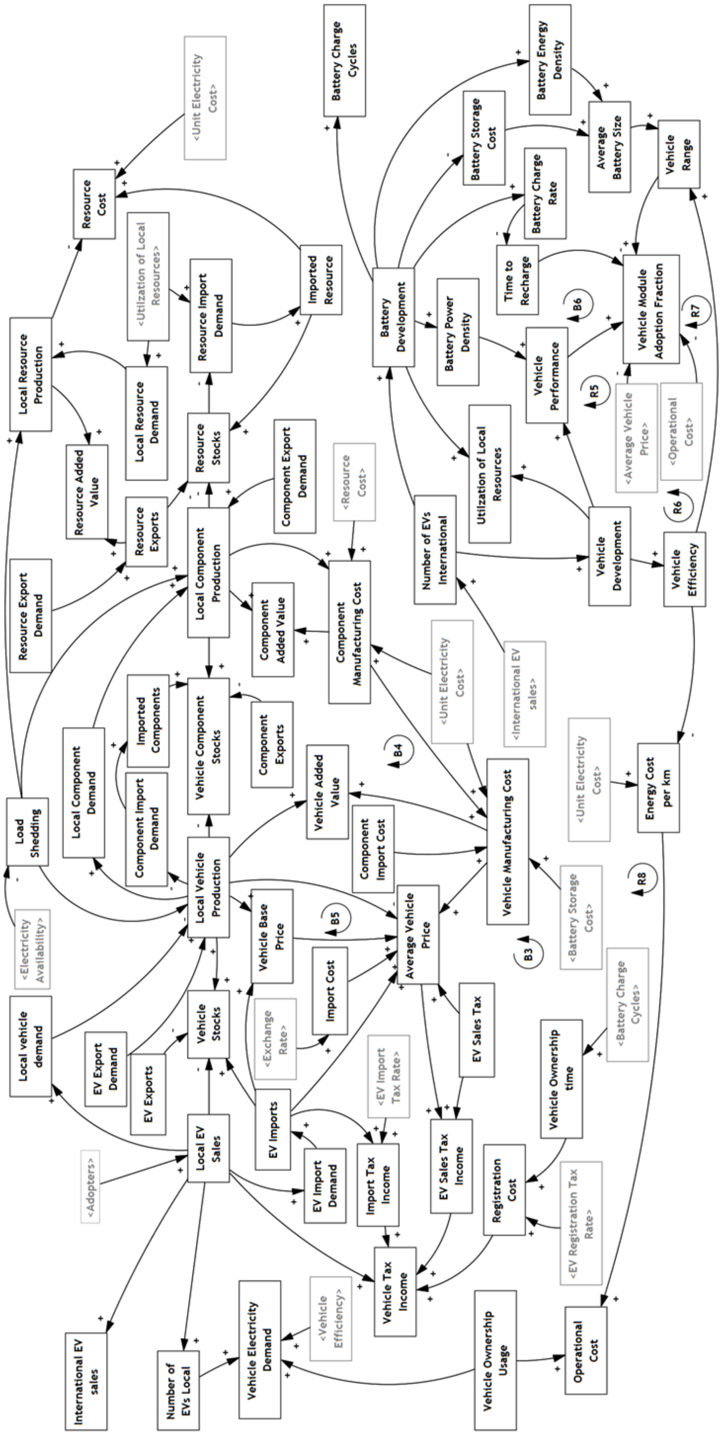

Figure 2: Vehicle module

4.4.2. Energy

For any EV to be manufactured or to operate, a stable, inexpensive, and convenient source of electricity must be available. The availability of electricity, the cost, and the ability to use it effectively to recharge one's vehicle are essential factors influencing EV adoption. The energy module is represented in Figure 3. The first part of this module that is investigated is vehicle charging.

As the number of EVs increases, so does the need for more electricity to power these vehicles. The electricity demand of EVs can be calculated by using the efficiency of the vehicles and the average distance travelled over a period. However, this calculated electricity demand is only a component in the electricity supply that enables the use of EVs. EVs would not fit into the local market puzzle without adequate electricity generation, distribution, and charging infrastructure.

Slow residential and public fast chargers are the main methods for consumers to recharge their EVs. The number of fast chargers is vital to increase the EV adoption rate. Yet a chicken-and-egg paradox arises: an increase in EVs on the road necessitates, and is facilitated by, an increase in public fast chargers to charge all of the vehicles. Many fast chargers are needed for consumers to trust the ability to charge their EVs using public charging infrastructure when necessary. Therefore, a reinforcement loop exists between the number of fast chargers, the adoption rate, and the number of EVs (R9). Increasing the number of fast chargers increases charger density if the country's population stays constant (R10). The increase in demand for new high-power fast chargers stimulates this product type's development. When combined with the increased charging speed of batteries, increased charger power would positively influence the adoption rate of EVs, thereby completing the reinforcement loop (R11). However, all of these chargers require a steady supply of electricity to function.

The increased number of EVs increases the total power used, reducing power availability. The decrease in availability would negatively affect the adoption rate, as there is a positive causal link between the two factors, thereby creating a balancing feedback loop (B7). However, the reduced electricity availability increases the cost of an electric power unit, subsequently negatively influencing the adoption rate.

When the electricity demand surpasses the total supply available, an electricity utility will implement loadshedding to affect an immediate load reduction in the national electrical grid to balance the available electricity supply and demand (B10). Such load reduction results in reduced economic output.

Low electricity availability is remedied by increasing the amount of electricity produced. If electricity availability decreases, the construction of electricity production capacity must be stimulated by increased grid-level capacity (B9) or small-scale embedded generation (SSEG). SSEG includes solar panels and wind turbines that supplement power consumption on a local level (B10).

4.4.3. Consumer module

The consumer module CLD in Figure 4 combines the influence of the other two modules on the individual consumer's characteristics. It provides a comprehensive perspective on the impact of urbanisation, social relations, academic education, and household income. These factors collectively shape consumer behaviour and influence their decisions. By examining these elements, we gain a deeper understanding of the dynamics at play in consumer attitudes and preferences.

An increase in the number of local EVs leads to a higher number of acquaintances with EVs who could influence the consumer to consider an EV (R12).

The jobs factor in this module represents the employment opportunities created within and beyond the system's boundaries, and is influenced by other modules. These relationships highlight the potential economic impact of EV adoption through job creation. The GDP factor represents the collective value added through product manufacturing, sales, and infrastructure construction. It measures the overall economic growth and development resulting from the EV ecosystem. The tax income factor represents the revenue generated across all three modules and beyond, reflecting the financial implications of EV adoption for tax revenues.

The consumer module incorporates the determination of effective GDP, which factors in the exogenous inflation rate. This calculation proves useful in assessing the motorisation rate of the population, providing insights into the level of vehicle ownership in relation to economic factors. The model also accounts for government policy creation, where tax rates influence various aspects of GDP and value creation in different sectors. Notably, tax rates related to purchasing new EVs and their yearly registration costs play a critical role. When the government identifies the potential for increased economic benefits through higher EV adoption, it may adjust these taxes downward, reducing the overall cost of purchasing and owning an EV.

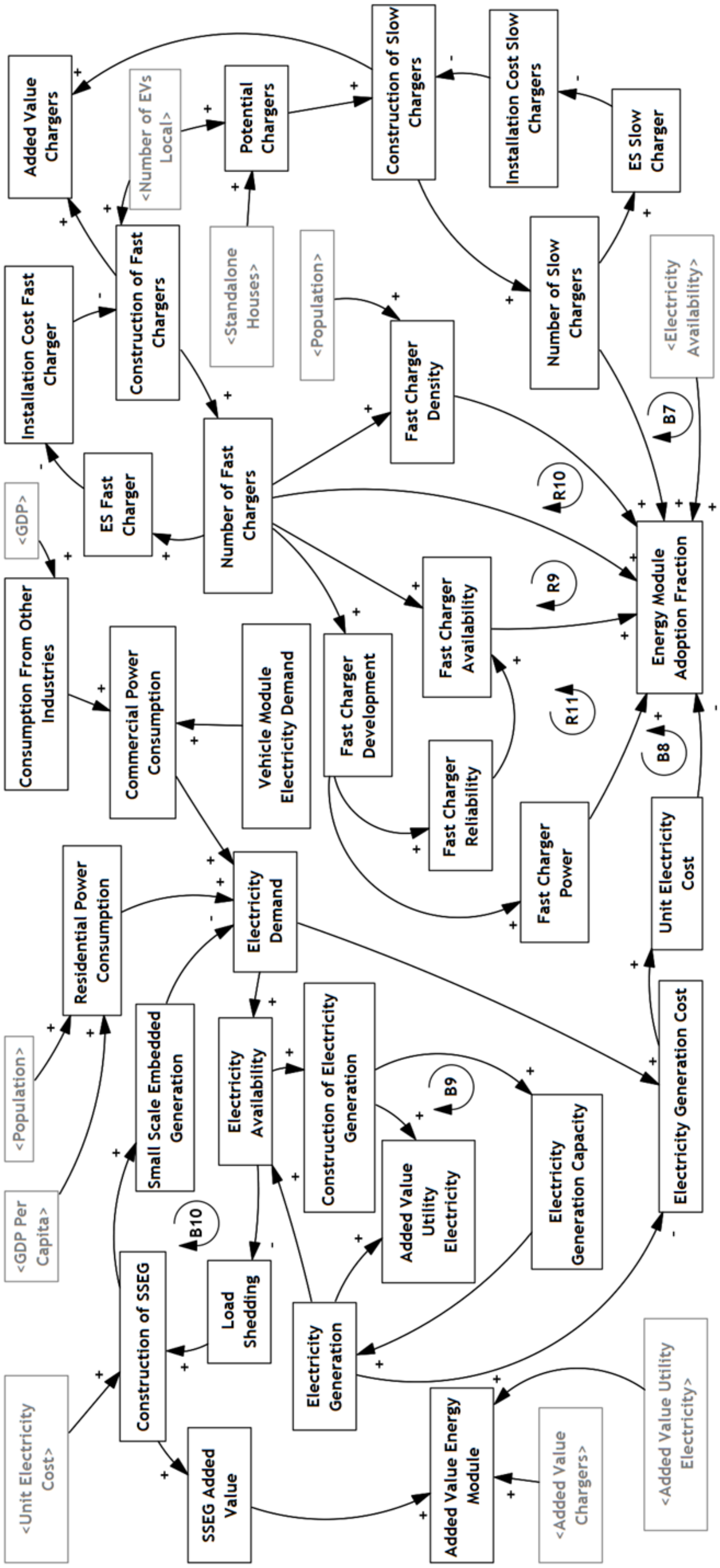

Figure 3: Energy module

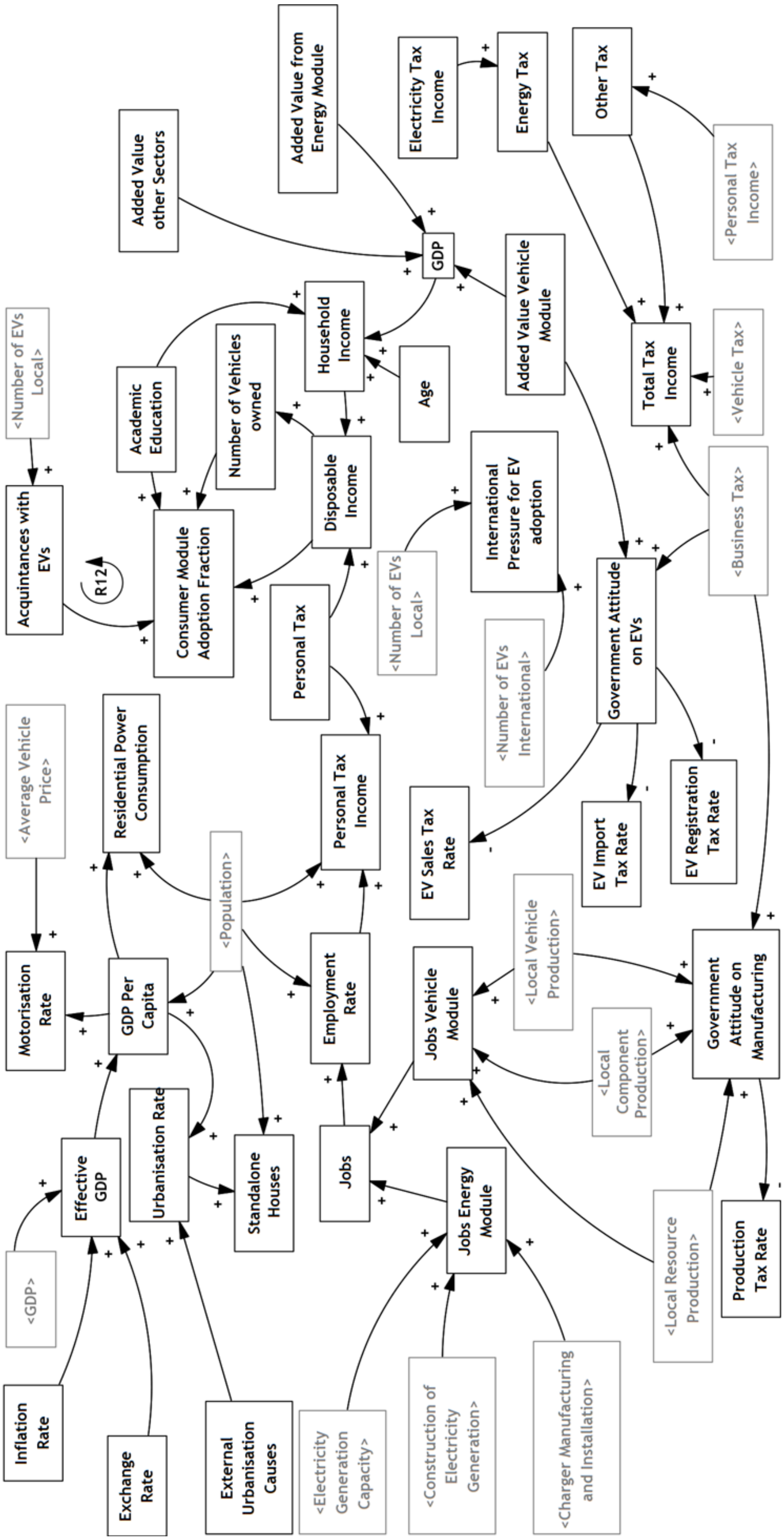

Figure 4: Consumer Module

5. ANALYSIS

The model can be analysed with the causal loop diagram of the factors that influence the adoption of EVs in South Africa. All three modules show similar relationships, such as economic contributions, job creation, and taxation. However, the three modules also display unique aspects that are noteworthy and that are analysed by exploring select factors and their relationships that have been identified to influence many factors downstream. A visual tracing of the qualitative model can be done of how each factor influences the next factor until the adoption rate factor in the model is arrived at. The impact of the relationships between factors was identified during the literature review, and considered when tracing the effect of the factors.

The overall CLD showcases the required interactions for s-shaped growth in EV adoption. In Figure 1, the initial impact of advertising could help to initiate growth in the number of EV adopters. Once the initial adoption has begun, the positive feedback loops that increase the adoption rate could increase the number of people who adopt EVs. Furthermore, the economic growth from the new vehicle manufacturing supply chain (from resource to finished vehicle) could increase the motorisation rate by increasing GDP per capita. The increased motorisation rate would stimulate movement from the general population stock to the stock of potential adopters. However, the adoption rate might then slow as the population who hadn't adopted EVs decreased. After a few decades, the growth and attrition rates of the population would most likely tend to equilibrium. The slowed growth in population might reduce the rate of increase of potential adopters. Therefore, a decrease in the adoption rate could be expected as the number of potential adopters decreased. Finally, a new equilibrium would probably be reached where the adoption rate converged with the population growth and the motorisation rate. The resulting adoption rate measured over time would have a strong potential to resemble an S-shaped curve.

In both the vehicle and the energy modules, taxation is an essential factor. It plays a crucial role in affecting the cost of a good. This cost is typically passed down to the consumer, limiting the number of goods they can purchase. In the case of vehicles, the high taxation has continued to place even smaller, less expensive EVs beyond the reach of wealthy consumers. Furthermore, taxation on constructing new electricity generation capacity could limit the amount of SSEG and large-scale power generation capacity.

The vehicle module is arguably the most important one in this model. The vehicle supply chain within this module presents an opportunity for growth as increased research into vehicle and battery technologies allows for increased localisation of production. This would be made possible by developing vehicle components made from materials sourced from the African continent and manufacturing methods that allowed profitable production with South Africa's relatively high labour cost. The cost of labour and the impact of taxation would be some factors that would influence the cost of production the most. In addition, employment opportunities in the vehicle supply chain would reduce unemployment and increase the country's GDP by purchasing goods and services. The increased expenditure on goods and services by the people employed in the vehicle supply would stimulate the growth of businesses to supply these goods and services, and therefore create more indirect employment opportunities.

The energy module illustrates the importance of increased energy capacity. When electricity demands are high and available supplies are low, loadshedding results. This directly influences consumers' trust in an electric vehicle solution. Loadshedding adversely affects the vehicle module and limits the availability of chargers. This results in a definitive increase in range anxiety. To address this problem, the construction of new electricity generation capacity would be required – be it from commercial power plants or SSEG. The construction of new electricity generation capacity would have definite benefits. Constructing new power generation capacity would reduce electricity prices by reducing the need for individual power plants to operate in their least cost-effective range.

In addition, increasing electricity generation capacity would contribute directly to the economy and treasury during construction and operation. As with the vehicle module, definite steps could be taken to reduce the cost of electricity production by reducing the taxation of electricity generation and storage equipment. This could help to accelerate the implementation of distributed energy solutions, and reduce the effective electricity demand, which, in turn, would help to increase energy availability. With reliable electricity available at a low cost at readily accessible recharging stations, consumers would be more likely to consider an EV.

The consumer module offers a glimpse into how the value creation, employment, and taxation in the energy and vehicle modules would affect the consumer. Furthermore, the impact of these factors on the government is illustrated. When setting policies (and subsequent taxes) for the various economic sectors, the government should consider the benefit it would create regarding tax income and economic growth. A delicate balance should be maintained, under ideal conditions, to grow the economy and have a positive impact on government.

6. CONCLUSION AND RECOMMENDATIONS

In this study, some of the main factors influencing the adoption of electric vehicles in South Africa were modelled using an adapted and shortened SD method. The identified factors and their reinforcement and balancing relationships were illustrated with a CLD qualitative model. The model analysis identified the potentially far-reaching impact of loadshedding and taxation on EV adoption. In addition, the potential to reduce unemployment, increase government income, and grow the economy through the local manufacturing of EVs was highlighted. Furthermore, the need for investment in infrastructure, specifically public fast-charging points, was noted.

These findings indicate a direct opportunity for both government and the private sector to leverage the factors under their control to increase South African consumers' ability realistically to consider purchasing an electric vehicle. The long-term benefit for businesses of investing in supporting infrastructure and local manufacturing would lead to wealth generation through increased value addition of products and infrastructure within South Africa's borders. The increased production of resources, parts, and vehicles, as well as the construction of infrastructure, could decrease unemployment by creating skilled employment opportunities. These skilled jobs would offer higher-than-average salaries to employees, thereby increasing the average household income in the local and national community. The increased income of consumers could then be used to purchase additional products and services, thereby stimulating employment opportunities in other economic sectors. The government, in turn, could create more favourable fiscal conditions in which individuals, companies, and organisations are incentivised to purchase EVs. These conditions could be created by reducing the tax placed on EVs to (or below) that of ICEVs, and by reducing the tax on small-scale and renewable electricity generation equipment. This would help to improve the adoption rate and subsequently increase investments in supporting infrastructure. In addition, the local production of electric vehicle manufacturing capacity and the construction of electricity generation capacity would be sped up.

The immense scale of vehicle markets and their influential components quickly became evident during the study. Therefore, it was necessary to focus only on the main factors and their immediately influential causal factors. Various follow-up research opportunities were identified during the study. First and foremost is the further development and simulation of the model produced in this study. Second, a study of how a reduction in taxation could influence the cost of electric vehicles and, subsequently, adoption of the technology could provide valuable insights. Third, research into how EV production in South Africa could stimulate resource extraction and consumption for component manufacturing in the Southern African region could identify unexplored investment opportunities. Finally, modelling the environmental impact of EVs on South Africa using South Africa's energy mix might yield exciting insights.

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