Peer review history for:

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HOW TO CITE:
The adoption of Vehicle-to-Anything (V2X) in South Africa will reduce the combined cost of embedded solar generation and driving [peer review history]. S Afr J Sci. 2026;122(1/2), Art. #23146. https://doi.org/10.17159/sajs.2026/23146/peerreview

The original manuscript for review is appended below.

Reviewer 1: Round 1
Date completed: 13 October 2025
Conflicts of interest: None

Recommendation: Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments
REVIEWER: Revisions required
Does the manuscript fall within the scope of SAJS? Yes/No
REVIEWER: Yes
Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone? Yes/No
REVIEWER: Yes
Does the manuscript contain sufficient novel and significant information to justify publication? Yes/No
REVIEWER: Yes
Do the Title and Abstract clearly and accurately reflect the content of the manuscript? Yes/No
REVIEWER: Yes
Is the research problem significant and concisely stated? Yes/No
REVIEWER: Yes
Are the methods described comprehensively? Yes/No
REVIEWER: Yes
Is the statistical treatment appropriate? Yes/No/Not applicable/Not qualified to judge
REVIEWER: Yes
Are the interpretations and conclusions justified by the research results? Yes/Partly/No
REVIEWER: Yes
Please rate the manuscript on overall contribution to the field Excellent/Good/Average/Below average/Poor
REVIEWER: Good

Please rate the manuscript on language, grammar and tone Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is the manuscript succinct and free of repetition and redundancies? Yes/No
REVIEWER: Yes
The number of tables in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
The number of figures in the manuscript is Too few/Adequate/Too many/Not applicable
REVIEWER: Adequate
Are the results and discussion confined to relevance to the objective(s)? Yes/No
REVIEWER: Yes
Is the supplementary material relevant and separated appropriately from the main document? Yes/No/Not applicable
REVIEWER: Yes
Please rate the manuscript on overall quality Excellent/Good/Average/Below average/Poor
REVIEWER: Good
Is appropriate and adequate reference made to other work in the field? Yes/No
REVIEWER: Yes
Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates? Yes/No/Not applicable
REVIEWER: Not applicable
If accepted, would you recommend that the article receives priority publication? Yes/No
REVIEWER: No
Are you willing to review a revision of this manuscript? Yes/No
REVIEWER: Yes
With regard to our policy on 'Publishing peer review reports', do you give us permission to publish your anonymised peer review report alongside the authors' response, as a supplementary file to the published article? Publication is voluntary and only with permission from both yourself and the author. Yes/No
REVIEWER: Yes
Comments to the Author: Areas for Improvement Language and Style: The paper is very readable, but several stylistic refinements could make it tighter: Replace repetitive phrasing such as "considerable techno-economic and technological barriers yet to be overcome" with a more concise form ("significant techno-economic barriers remain"). Be consistent in terminology: Use SSES or SSEG consistently. Use V2G vs. V2X carefully — sometimes they're used interchangeably, sometimes not. In the abstract, include a specific quantitative statement of results (e.g., "V2G-enabled BEV households achieved cost parity with ICE households at ZAR xxx per annum"). Also add a policy takeaway sentence at

the end (e.g., “This study suggests that supportive V2G metering and tariff policies could accelerate BEV adoption in emerging markets.”)

Please provide some clarification on weather LCOE/LCOD were computed via simulation, spreadsheet model, or existing software.
Include a brief paragraph on sensitivity analysis — e.g., varying battery lifespan or tariff rates.
This would strengthen the robustness of conclusions.
Your discussion provides excellent insights, but it can be tightened for focus.

In the conclusion, I suggest adding numerical confirmation of key claims:
“Use Case 5 (SSES + BEV + V2G) achieved cost parity with ICE/grid baseline, with total AW of ZAR X vs. ZAR Y.”
End with a policy-oriented final statement

Minor Editorial Notes:
“update of BEVs” Should be “uptake of BEVs”
“Th use cases…” Typo “The use cases…”
Ensure all references have consistent journal name capitalization and year formatting.
Use consistent formatting for Units such as kWh, ZAR, °C, etc.
Define acronyms once and use consistently (SSES/SSEG, ICE, LCOD, FDS)
Proofread for typos, acronym consistency, and stylistic uniformity.

Author response to Reviewer 1: Round 1

Language and Style The paper is very readable, but several stylistic refinements could make it tighter: Replace repetitive phrasing such as “considerable techno-economic and technological barriers yet to be overcome” with a more concise form (“significant techno-economic barriers remain”)

AUTHOR: The whole paper has been edited to remove awkward phrases. This particular sentence has been amended to read:
“However, there are considerable techno-economic and technological barriers yet to be overcome before the adoption of BEVs becomes widespread in many countries.”

Be consistent in terminology: Use SSES or SSEG consistently. Use V2G vs. V2X carefully — sometimes they’re used interchangeably, sometimes not.

AUTHOR: Thank you. SSEG is no longer used in the article since I am referring only to SSES. I have also removed most of the references to V2X since its inclusion is not central to the arguments and the narrative is easier to follow without the V2L or V2X complication.

In the abstract, include a specific quantitative statement of results (e.g., “V2G-enabled BEV households achieved cost parity with ICE households at ZAR xxx per annum”). Also add a policy takeaway sentence at the end (e.g., “This study suggests that supportive V2G metering and tariff policies could accelerate BEV adoption in emerging markets.”)

AUTHOR: Thank you. The abstract has been rewritten to simplify the introductory sentences and to add more information on the results. The new text reads:
“Battery Electric Vehicles (BEVs) are essential to global decarbonisation roadmaps and are being increasingly adopted in many countries. However, significant techno-economic barriers remain before the adoption of BEVs becomes widespread in the Global South. Issues include higher costs, grid instability due to high electricity demand during peak periods, lack of recharging infrastructure and restrictive driving ranges relative to internal combustion engines (ICE). V2G can play a critical part in load balancing (peak shaving) and reducing costs for BEV owners. In this study, the potential of V2G is explored in more detail, looking at the development of appropriate hardware and software for V2G, the techno-economic assessment of V2G from a user and system perspective, and policy measures to support uptake of electric vehicles. The study shows that V2G-enabled BEV households achieve cost parity with ICE households. It concludes that systems which connect BEVs to V2G, and supportive V2G metering and tariff policies, would accelerate BEV adoption in emerging markets.”

Please provide some clarification on whether LCOE/LCOD were computed via simulation, spreadsheet model, or existing software.

AUTHOR: A short methodology paragraph has been added in the section on the techno-economic model. The modelling work was performed using a spreadsheet with hourly data recorded from a single system over a full year of operation.

Include a brief paragraph on sensitivity analysis — e.g., varying battery lifespan or tariff rates. This would strengthen the robustness of conclusions

AUTHOR: A new subsection has been added under the Results section covering the outcome of a sensitivity analysis.

Your discussion provides excellent insights, but it can be tightened for focus.

AUTHOR: The discussion section has been rewritten, making it shorter and focused only on the main research question in the study (the integration of BEV and SSES will reduce the costs for homeowners of their existing electricity use and their levelised cost of driving).

In the conclusion, I suggest adding numerical confirmation of key claims: "Use Case 5 (SSES + BEV + V2G) achieved cost parity with ICE/grid baseline, with total AW of ZAR X vs. ZAR Y."

AUTHOR: A new sentence has been added to the conclusion giving this result, modest as it is.

End with a policy-oriented final statement

AUTHOR: The final paragraph has been modified as follows:

The relatively small differences between the use cases suggest that economic factors alone are unlikely to adequately incentivise BEV uptake. Despite the advantages of V2G and BEVs in a sustainable energy future, their widespread adoption faces several challenges which must be addressed through collaboration between industry stakeholders, policymakers, regulators. In terms of further work, improvements to battery cycle life are necessary, and further research is required to assess a more diverse range of battery materials. Moreover, the South African government needs to implement the policy actions of its Electric Vehicles White Paper which include the scale up of investment in charging infrastructure, supporting localisation, expanding grid capacity and introducing consumer incentives [45].

Minor Editorial Notes: "update of BEVs" Should be "uptake of BEVs" "Th use cases…" Typo "The use cases…" Ensure all references have consistent journal name capitalization and year formatting. Use consistent formatting for units such as kWh, ZAR, °C, etc. Page 3 of 5

Define acronyms once and use consistently (SSES/SSEG, ICE, LCOD, FDS) Proofread for typos, acronym consistency, and stylistic uniformity.

AUTHOR: Thank you for all these notes. Apologies for the initially careless proofreading.

Reviewer 2: Round 1
Date completed: 06 October 2025
Conflicts of interest: None

Recommendation:
Accept / Revisions required / Resubmit for review / Resubmit elsewhere / Decline / See comments

REVIEWER: Revisions required

Does the manuscript fall within the scope of SAJS?
Yes/No

REVIEWER: Yes

Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone?
Yes/No

REVIEWER: Yes

Does the manuscript contain sufficient novel and significant information to justify publication?
Yes/No

REVIEWER: Yes

Do the Title and Abstract clearly and accurately reflect the content of the manuscript?
Yes/No

REVIEWER: Yes

Is the research problem significant and concisely stated?
Yes/No

REVIEWER: Yes

Are the methods described comprehensively?
Yes/No

REVIEWER: Yes

Is the statistical treatment appropriate?
Yes/No/Not applicable/Not qualified to judge

REVIEWER: Not applicable

Are the interpretations and conclusions justified by the research results?
Yes/Partly/No

REVIEWER: Yes

Please rate the manuscript on overall contribution to the field
Excellent/Good/Average/Below average/Poor

REVIEWER: Good

Please rate the manuscript on language, grammar and tone
Excellent/Good/Average/Below average/Poor

REVIEWER: Excellent

Is the manuscript succinct and free of repetition and redundancies?
Yes/No

REVIEWER: Yes

The number of tables in the manuscript is
Too few/Adequate/Too many/Not applicable

REVIEWER: Adequate

The number of figures in the manuscript is
Too few/Adequate/Too many/Not applicable

REVIEWER: Adequate

Are the results and discussion confined to relevance to the objective(s)?
Yes/No

REVIEWER: Yes

Is the supplementary material relevant and separated appropriately from the main document?
Yes/No/Not applicable

REVIEWER: Yes

Please rate the manuscript on overall quality
Excellent/Good/Average/Below average/Poor

REVIEWER: Good

Is appropriate and adequate reference made to other work in the field?
Yes/No

REVIEWER: Yes

Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates?
Yes/No/Not applicable

REVIEWER: Not applicable

If accepted, would you recommend that the article receives priority publication?
Yes/No

REVIEWER: No

Are you willing to review a revision of this manuscript?
Yes/No

REVIEWER: Yes

With regard to our policy on 'Publishing peer review reports', do you give us permission to publish your anonymised peer review report alongside the authors' response, as a supplementary file to the published

article? Publication is voluntary and only with permission from both yourself and the author.
Yes/No

REVIEWER: Yes

Comments to the Author:

The authors explore the consequences (mostly financial) of enabling South African households to use a car battery to feed back into the grid or use the car battery for household consumption (also integrated to a solar system). They present a simple model that highlights current opportunities and challenges, and that also could be adapted to test more specific scenarios.

The paper is clearly written and the topic is ideal for SAJS in that it is relevant (and of significant interest) locally and of broader interest. I would only recommend relatively minor modification that should also address the following:

1. At the moment too many aspects of the article are generic and would probably apply to almost any country. Please make the article more specific to South Africa by adding a more in-depth description of the roll-out of electric vehicles in the country (e.g. how many have been imported to date, and what are the local projections). Also say a bit more about the local developments in EV's, e.g. how many charging stations currently exist, and how many are planned.
2. South Africa is a very diverse country in terms of weather patterns and their seasonality (and hence solar potential). This means that the type of calculations performed here may look very different in some places. It may not be the case, but I sometimes got the sense that the calculations were based in conditions as they pertain in the Western Cape. It would go beyond the scope of this paper to make regionally-based calculations, but there needs to be an acknowledgement of the diversity in conditions and that this could substantially affect the results for specific locations.
3. Other smaller points:
    - Line 45 - The phrase "vehicles using an internal combustion engine (ICE) are no longer in use" may be ambiguous. Maybe reword to "before vehicles using an internal combustion engine (ICE) are no longer in the majority", or something to that effect.
    - Line 60-61 - I think the following sentence formulation would sound better: "and in the event that daily distances travelled are mostly below the energy storage capacity of the vehicles".
    - Line 92 - Reference is needed for the size of SA vehicle fleet.
    - Line 175 - It might be worthwhile reminding readers what LCOD and TCO stand for.
    - Line 190, 201 - I imagine that t and n are measured in years. I think that should be stated explicitly.
    - Line 236 - "The used cases ..."
    - Lines 284-289 (also line 365) - That may be the case for Cape Town, but in the South African Interior solar yield is often higher in winter than in summer (summer rainfall; shorter days, but almost guaranteed sunshine in winter). Difficult to quantize this for calculations, but it should at least be mentioned in a qualitative way.

Author response to Reviewer 2: Round 1

The paper is clearly written and the topic is ideal for SAJS in that it is relevant (and of significant interest) locally and of broader interest. I would only recommend relatively minor modification that should also address the following (Author – see below).

AUTHOR: Thank you for this affirmative comment. All the requested modifications, together with the author's changes, are listed below.

At the moment, too many aspects of the article are generic and would probably apply to almost any country. Please make the article more specific to South Africa by adding a more in-depth description of the roll-out of electric vehicles in the country (e.g. how many have been imported to date, and what are the local projections). Also say a bit more about the local developments in EV's, e.g. how many charging stations currently exist, and how many are planned.

AUTHOR: A new section has been added at the end of the literature section describing this context, as

follows:
Similarly, the uptake of BEVs in South Africa remains restricted. According to the National Association of Automobile Manufacturers of South Africa 32, 1,257 BEVs were sold in South Africa in 2024 (annualised from Q1 2024 data), representing 11% of the sales of all new energy vehicles and only 0.24% of all new vehicle units. Although sales are growing, the volumes are small, as is the charging infrastructure. There are 500 public charging stations, mostly along the major transport routes and in the metropolitan areas [33].

South Africa has taken an important step towards incentivising green mobility by introducing a 150% tax incentive for electric and hydrogen vehicle production. The allowance, announced by the Minister of Finance in his 2024 budget speech [34] and introduced in 2025, is expected to stimulate the country's nascent BEV industry, encourage investment, and position South Africa as a key regional player in the global shift toward sustainable transport. The new incentive offers manufacturers tax breaks on research, development and production costs, thereby accelerating the domestic production of EVs and hydrogen-powered vehicles, as well as the components needed for their assembly.

South Africa is a very diverse country in terms of weather patterns and their seasonality (and hence solar potential). This means that the type of calculations performed here may look very different in some places. It may not be the case, but I sometimes got the sense that the calculations were based in conditions as they pertain in the Western Cape. It would go beyond the scope of this paper to make regionally based calculations, but there needs to be an acknowledgement of the diversity in conditions and that this could substantially affect the results for specific locations.

AUTHOR: This is an important point – the conditions in Limpopo are different with lower annual variations. Two additional references [below] have been added to the discussion section and a short paragraph about the extent of diversity and its impact on solar PV.

- Singh J. Ranking South African provinces on the basis of MERRA 2D surface incident shortwave flux. Journal of Energy in Southern Africa. 2016;27(3):50-7.
- Boateng L, Mhangara P. A Comparative Assessment of Annual Solar Irradiance Trends between Mpumalanga and Northern Cape Province in South Africa Using PVGIS. Energies. 2023;16(18):6665.

Other smaller points:
Line 45 - The phrase "vehicles using an internal combustion engine (ICE) are no longer in use" may be ambiguous. Maybe reword to "before vehicles using an internal combustion engine (ICE) are no longer in the majority", or something to that effect.

AUTHOR: The sentence has been rephrased to:
“However, there are considerable techno-economic and technological barriers yet to be overcome before the adoption of BEVs becomes widespread in many countries and before vehicles using an internal combustion engine (ICE) are obsolete.”

Line 60-61 - I think the following sentence formulation would sound better: "and in the event that daily distances travelled are mostly below the energy storage capacity of the vehicles".

AUTHOR: The sentence has been changed to read:
“Given that for much of the day, passenger vehicles are not being used and, in the event that daily distances travelled are below the energy storage capacity of the vehicles, BEVs have stored but surplus energy.

Line 92 - Reference is needed for the size of SA vehicle fleet.

AUTHOR: Thank you … a new reference has been added.

Line 175 - It might be worthwhile reminding readers what LCOD and TCO stand for.

AUTHOR: The acronyms have been redefined here as well to assist the reader.

Line 190, 201 - I imagine that t and n are measured in years. I think that should be stated explicitly.

AUTHOR: *t* has been added to the list of symbols. Both t and n have been stated as years.

Line 236 - "The use cases ..."

AUTHOR: Th has been changed to The use cases …

Lines 284-289 (also line 365) - That may be the case for Cape Town, but in the South African Interior solar yield is often higher in winter than in summer (summer rainfall; shorter days, but almost guaranteed sunshine in winter). It is difficult to quantify this for calculations, but it should at least be mentioned in a qualitative way.

AUTHOR: I have added the phrase ‘depending on the climatic conditions’ and then a further section in the Discussion as follows:

This result is particularly relevant to the Western Cape with its higher diversity between winter and summer solar irradiance conditions (references added). As already noted, SSES systems tend to be sized for winter conditions, implying that a large amount of excess solar is available in the summer months, which can be usefully stored in a BEV. A similar conclusion, but with a lower net benefit, can also be reached for systems in all regions of South Africa, including commercial buildings which have a high daylight-hours energy consumption.

The Adoption of Vehicle-to-X in South Africa Will Reduce the Combined Cost of Embedded Solar Generation and Driving

Abstract

Battery Electric Vehicles (BEVs) are essential to global decarbonisation roadmaps and are being increasingly adopted in many countries. However, there are considerable techno-economic and technological barriers yet to be overcome before the adoption of BEVs becomes widespread in the Global South. Issues include grid instability due to high electricity demand during peak periods, lack of recharging infrastructure, high battery costs and limited lifetimes, restrictive driving range, long recharging times and high levelised cost of transport or total cost of ownership relative to internal combustion engines. V2G can play a critical part in load balancing (peak shaving), delivering incentives to owners for the update of BEVs, storing excess renewable energy, improving overall grid operations and decreasing the overall electricity cost. In this study, the potential of V2G is explored in more detail, looking at the development of appropriate hardware and software for V2G, the techno-economic assessment of V2G from a user and system perspective, strategies for acceptance of the technology within South Africa and policy measures to support uptake of electric vehicles. It is concluded that connection between BEVs and multiple energy needs (V2X) could help to finance BEV uptake given that BEV ownership linked to small-scale embedded solar systems is presently inaccessible for many households.

Significance:

- Small scale embedded solar (SSES) is an expensive option for homeowners; the levelised cost of energy is double the cost of power from Eskom.
- Vehicle-2-Grid (V2G) is an attractive option for SSES owners if the vehicle is charged from SSES during the day.
- The calculated annual worth of a BEV with SSES is equivalent to the base case of a fossil fuel-based vehicle and grid-based energy.
- Using an optimal charging strategy, BEVs can reduce grid-based electricity demand and travel costs.
- Bidirectional metering, multiple energy use (V2X) and time-of-use tariffs will be essential for the migration to BEVs.

Keywords: vehicle to grid, grid interconnection, battery electric vehicle, annualised cost

Introduction

Battery Electric Vehicles (BEVs) are an essential component of global initiatives to decarbonise socio-technical systems and particularly systems of mobility [1-3]. By the end of 2023, there were already 40 million electric vehicles on the road and the number is predicted to grow to 250 million by 2030 [4]. Sales of electric vehicles have grown exponentially, reaching nearly 15 million in 2023, with about 60% of the sales attributed to China [5].

However, there are considerable techno-economic and technological barriers yet to be overcome before the adoption of BEVs becomes widespread in many countries [6,7] and vehicles using an internal combustion engine (ICE) are no longer in use. Issues include the high initial BEV cost, grid instability due to high electricity demand during peak periods, lack of recharging infrastructure, high battery costs and limited lifetimes, restrictive driving range, long recharging times and high levelised cost of driving (LCOD) or total cost of ownership (TCO) relative to internal combustion engines [8-10].

One solution to these issues, already widely explored and reported in the literature, is the adoption of Vehicle-to-Grid (V2G) technology [11], or more broadly Vehicle-to-Anything (V2X), where X includes multiple sources of demand such as residential or commercial properties, mobile homes and off-grid machinery. Examples of new applications include Vehicle-to-Building (V2B), Vehicle-to-Load (V2L), Vehicle-to-Home (V2H) and Vehicle-to-Infrastructure (V2I) [12].

V2G is the integration of BEVs within an electricity grid in a way that allows vehicle owners to sell energy from the BEV batteries to utility companies. Given that for much of the day, passenger vehicles are not being used [13] and that daily distances travelled are mostly below the energy storage capacity of the vehicles, BEVs have stored but surplus energy which could be used elsewhere, such as for domestic needs or for supplying the wider energy grid [14,15].

At the core of V2G are two devices; the bidirectional V2G unit, which allows both energy charging and discharging, and the bidirectional smart meter, which measures the quantity and calculates the cost of the energy transactions (see Figure 1). By supplying energy to a (micro)grid, the vehicle owner can participate in energy trading and much-needed income, perhaps up to 12 % of the annual equivalent of the car's initial cost [16]. Alternatively, the stored energy could be used by vehicle owners to supply their own domestic needs, replacing more expensive energy drawn from the grid during times of peak demand.

V2G can, therefore, play a critical part in load balancing, frequency regulation, acting as a spinning reserve, delivering incentives to owners for the update of BEVs, storing excess renewable energy, improving overall grid operations and decreasing the overall electricity cost [5,12,17,18].

In a research project, the results of which are reported in this article, we explored in more detail the potential for South Africa of V2G, looking at the development of appropriate hardware and software for V2G, the techno-economic assessment of V2G from a user and system perspective, what strategies could be used to increase acceptance of the technology within South Africa including necessary policy measures and finally, how to increase community-level energy security and resilience within a context of increasing energy poverty and insecurity using V2G. The study assumed a behind-the-meter architecture for V2G as shown in Figure 1.

Literature Review

V2G Technology and Cost

V2G, and more broadly V2X, have been under consideration as a useful means of accessing additional energy storage since the late 1990s [15]. Compared to small-scale embedded solar system (SSES), BEVs are equipped with large batteries. A typical SSES will deploy a battery capacity of 10 kWh to 20 kWh whereas BEVs have capacities of 40 kWh to 100 kWh. Even for a small country like South Africa, which has a fleet size of about 12 million vehicles, the total sum of stored energy will amount to 840 GWh, if 100% conversion to BEVs will take place before the 2050 Net Zero date. Given that South Africa has an annual electricity demand of 195 TWh [19], the energy stored in BEVs represents about 38 hours of electricity supply for the entire country.

These calculations are presented not to suggest that BEVs could be used as GW scale energy storage schemes, but rather to highlight that V2G does offers an opportunity for utility companies to access infrastructure necessary to maintain a reliable energy supply without incurring the associated capital costs [5]. Such storage could enhance grid stability, mitigate supply/demand imbalances, act as devices for valley filling and peak shaving, and regulate electricity frequency [17]. The benefits of V2G for vehicle owners, and especially the benefit to cost ratio is more complicated. Although any additional revenue from energy sales is a clear benefit, it comes at the cost of reduced battery lifetimes and the inconvenience of more careful energy management [5].

The adoption of V2G has required significant technological innovation in areas such as the interconnection between the vehicle and the charging/discharging stations, on-board modulation of the energy format, net metering solutions for vehicle owners and grid operators, and efficient battery management software. Some progress has already been made, and further developments are underway. For instance, several of the larger vehicle manufacturers have already released versions of V2G onto the market, for instance:

- *Nissan*: Nissan will launch its V2G technology in 2026, allowing BEV owners to power their homes during peak times or outages from their vehicle's battery, and allow them to sell surplus energy back to the grid [20]
- *Ford*: Ford has launched the Ford F-150 Lightning which is an electric pick-up equipped with bidirectional charging capability and a 100 kWh battery pack [21]. Ford is also the Ford is a co-founder of ChargeScape, a software company that provides the technology to support smart metering and bidirectional energy trading.
- *Volkswagen*: Volkswagen's ID.4 can discharge power for various applications [22].
- *Hyundai*: Hyundai has developed the Electric-Global Modular Platform which together with the Integrated Charging Control Unit can support bidirectional charging [23].
- *BYD*: Many of the BYD models include facility for vehicle to load (V2L) energy transfer, which uses a standard charge cable to supply direct current.

Progress in the development and commercial availability of smart bidirectional meters is more limited. The essential features of bidirectional meters are to measure positive and negative energy flows, allow time-of-use billing and optimise the use of energy according to the cost of the various sources. In Australia, new chargers, such as the Sigenergy's SigenStor and RedEarth's Ambibox DC Wallbox, are entering the market, supporting V2G and V2H [24]. In the USA, General Motors offers a complete energy home system including the charger, the power bank and the inverter, with metering capability.

The cost of V2G is still high due to the additional investment in home infrastructure (electrical) and the reduced battery lifespan. For instance, Anil Paryani, Executive Director of Engineering at Ford Motor Company, recently reported that the additional cost to the prosumer of V2G is about ZAR 3 per kWh due to the battery replacement charge [25]. Other authors are less pessimistic, arguing that the studies are inconclusive and that car manufacturers would not be offering V2X unless the problem of battery lifespan had been solved [3]. In this study, a limited degree of degeneration has been included as per a prior techno-economic study of BEVs as distributed energy storage systems [5].

V2G Frameworks and Regulations

China leads the world in BEV sales, as noted in the introduction, and is also one of the leading countries in the adoption of V2G frameworks and regulations with plans for complete V2G integration by 2023 [5]. The plans include guidelines for the acceleration of national and industry standards for V2G, focusing on interaction interfaces and communication protocols, the development of advanced battery technology to support high cycling usage, the further commercialisation of bidirectional meters, the implementation of time-of-use electricity pricing policies for residential charging facilities, the launch of several V2G demonstration projects in different locations and user communities, and support for electricity grid operators in V2G management and energy trading [26].

In South Africa, the context for V2G is framed by two distinguishing features. Firstly, the Eskom generation crisis accelerated the installation of SSES, with the latest estimates indicating that the total installed capacity had exceeded 5 GW by mid-2024 [27,28]. The second feature is that the installations are highly uneven between different income groups, and have further increased the inequality between high and low income households [29]. The dominant reason for the installation of SSES has not been directly linked to a net zero energy transition but instead by a distrust amongst energy customers in the national utility. Future policies to support a e-mobility transition needs to increase EV uptake but also ensure an inclusive rate of adoption [30].

South Africa has taken an important step into the future of green mobility by introducing a 150% tax incentive for electric and hydrogen vehicle production. The legislation, signed into law in early 2025, is expected to stimulate the country's nascent BEV industry, encourage investment, and position South Africa as a key regional player in the global shift toward sustainable transport. The new incentive offers manufacturers tax breaks on research, development and production costs, thereby accelerating the domestic production of EVs and hydrogen-powered vehicles, as well as the components needed for their assembly.

Techno-Economic Model and Use Cases

Calculations for Levelised Costs

The model is based on three separate technoeconomic analyses, the levelised cost of energy (LCOE) [31,32], LCOD [33,34] and TCO [10]. All these approaches are well described in the literature. The common feature of their algorithms is to convert all costs into a net present value, (TCO in the case of vehicle ownership), and then divide this amount by the discounted sum of

distance travelled, in the case of LCOD, or discounted sum of energy generated/used, in the case of LCOE. The equations for LCOE and LCOD are given below [35].

Equation 1

$$LCOE = \frac{Sum\ of\ the\ Discounted\ Values\ of\ Costs\ over\ Lifetime\ of\ SSEG}{Sum\ of\ the\ Discounted\ Output\ of\ Energy\ over\ Lifetime}$$

$$= \frac{\sum_{t=1}^{n} \frac{I_t + M_t - R_t + O_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where:

I_t = investment expenditure in year t (ZAR)

M_t = maintenance expenditure in year t (ZAR)

R_t = energy rebate in year t (ZAR)

O_t = operational expenditure in year t (ZAR)

r = discount rate

n = expected lifetime of the system

E_t = energy output in year t (kWh)

Equation 2

$$LCOD = \frac{Sum\ of\ the\ Discounted\ Values\ of\ Costs\ over\ Lifetime\ of\ BEV}{Sum\ of\ the\ Discounted\ Output\ of\ Distance\ Travelled\ over\ Lifetime}$$

$$= \frac{\sum_{t=1}^{n} \frac{I_t + M_t + O_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{D_t}{(1+r)^t}}$$

where:

I_t = investment expenditure in year t (ZAR)

M_t = maintenance and insurance expenditure in year t (ZAR)

O_t = operational expenditure (fuel) in year t (ZAR)

r = discount rate

n = expected lifetime of the system

D_t = distance driven in year t (km)

In the calculation of the net energy cost, the grid-related costs such as the purchase of energy from the grid (based on unit fees) and the connection fees must be added. The net LCOE is obtained as the weighted average of energy from the SSES and the grid. It is also necessary to adjust for the energy losses due to battery roundtripping and the use of an inverter [36]. For

the SSES, the overall energy efficiency is about 90%; in other words, 10% of the energy input from the two sources (grid and solar) is lost to the inverter and stationary battery. A similar value is also applied to the energy efficiency of the BEV charging/discharging cycle.

As the final step in the sequence of calculations to support the comparison between the five different use cases explored in this study, the LCOE and LCOE are converted to their respective annual worth (AW) values by multiplying the individual values by the total electricity demand and distance travelled respectively. Annual worth is a routine financial calculation which reduces all costs to single year values and allows comparative assessment between different options for engineering systems [37].

Definition of Use Cases

Five different use cases were explored in the modelling studies, as shown in Table 1. It is noted that there is an important difference between grid-tied and grid-connected. The former refers to a grid interface between the SSES and the grid which allows bidirectional flow through a smart meter, whereas the latter only allows unidirectional flow from the grid to the SSES.

The system specifications for the five use cases are listed in Table 2. There are probably as many use cases as there are users in a national electricity system. Each user will have a different and perhaps unique energy demand, depending on factors such as work patterns, domestic habits, energy budget, location and building design. The model itself was built to accommodate variable patterns of use and solar energy, with the raw data requirement being the hourly values for measured solar irradiance (or potential solar panel output), actual solar energy generated/used, grid consumption and total energy demand.

An important consideration for the analysis is the daily period over which BEV charging will take place. The study has focussed on the optimal conditions within which V2G could be economic, making maximum use of the available solar generation and minimising any additional energy demand from the grid. Th use cases in this study all assume that BEV charging will take place over the peak solar generation period, as is discussed in more detail in Section 4.1. In this way, drawing additional energy from the electricity grid will largely be avoided, and the homeowner will make maximum use of embedded generation. For a household with an existing SSES, this energy is essentially without cost and is a direct subsidy of the BEV.

The use of the vehicle as assumed in this analysis is based on the pattern of a single car household in which one person works from home and the other members are either at school or need transport to a local place of employment. Serving these needs therefore requires two daily trips, each of 25km, one early in the morning and one in the late afternoon.

The technical specifications for the vehicles evaluated in the study have been taken from multiple sources including TechCentral[38] and manufacturers' brochures (VW Polo Sedan 81kW 1.6 Tipt and BYD Dolphin Premium). These choices are small cars which align with the vehicle use cases as defined in the earlier discussion. The BYD Dolphin Premium is equipped with a 60.5 kWh battery and a V2X discharge adapter.

Financial Data

The input financial assumptions as used for the techno-economic modelling have been listed in the Supplementary Material. Standard values have been assumed for the common parameters such as project duration, maintenance and capital costs. It is noted that the financial calculations are all based on real 2024 South African Rands (ZAR) since the levelised cost methodology cannot deal with inflation. For this reason, the discount rate is a real rate, rather than nominal, and is set at 8.5%.

There are two other relevant considerations for this study. Firstly, photovoltaic panel efficiencies are sensitive to heat and decrease over time, as reported in the literature [39]. Secondly, battery lifespans are reduced proportional to the number of charge/discharge cycles. The reduction in panel efficiencies has been ignored in the study since the impact is minimal. However, the cost of the battery deterioration has been included by tracking the number of charge/recharge cycles and then adding additional maintenance cost in proportion to the number of necessary replacements over the project period, as per literature values [5].

The cost of BEVs vs. the stationary batteries in SESS make the latter appear overpriced. Battery costs are highly modular – a 20 kWh battery costs double a 10 kWh unit, and so on. A BEV containing 60 kWh of battery storage has the equivalent of ZAR 312,000 worth of storage, which is 66% of the full cost of the BEV (in this case for the BYD Dolphin Premium). The price differential suggests that the cost of stationary battery systems will also decrease in the future.

Results

Solar Availability and Vehicle Charging

In a prior analysis using the same input date for generation/demand, it has been shown that a typical SSES installation will have as much as 50% excess capacity (unused solar) [28]. However, the energy is not available at all times of the day; typically, the excess supply will be available between the hours of 10h00 to 16h00, indicating that the optimal BEV charging strategy will be during these hours.

As expected, the additional demand from the BEV reduces energy curtailment during summer and increases the energy drawn from the grid in winter. The latter impact is expected, since there is no available solar over the winter period since the panels are sized for zero surplus. The predicted profile for energy demand by the two different consumption points (vehicle and household), and the source of energy from which this demand is served, are shown in Figure 2.

Levelised Costs and Annual Worth

Use Case 1 considers the base conditions under which a household is grid-connected, drawing energy directly from the national utility, and uses a 1600 ICE for domestic use. This option has the lowest cost based on the sum of the AW values for electricity and transport, as shown in Table 3. In other words, the lowest cost option for households able to afford the purchase of a vehicle, regardless of the fuel it uses, is the conventional situation of grid-connected electricity supply and ICE. Interestingly, the cost of mobility is nearly six times higher than the cost of electricity in all cases. The annual fuel cost, in the case of an ICE, alone exceeds the cost of electricity usage.

Use Case 2, in which the household invests in the grid-connected purchase of SSES, is the most costly due to the high LCOE for SESS-generated energy, as already reported [28]. In the absence of bidirectional metering and energy rebates, SSES is economically unattractive and its uptake in South Africa has been driven by issues of energy security rather than reduced environmental impact or affordability. The higher energy costs are somewhat mitigated in the case of grid-tied SSES (Use Case 3), which reduces the net energy cost by 16% and increases the solar utilisation from 48% to 100%. However, the total AW remains higher than Use Case 1.

In summary, SSES based on a set of standard design considerations adds 80% to the annual cost of a household's electricity bill and does not ensure total independence from Eskom. The

optimal configuration ensures that the solar panels deliver sufficient energy during a winter's day (sunny conditions) to meet the daily average electricity needs, and that the overall systems (panels with the inverter and battery) is sized to meet a FDS value of 80%. The LCOE for a grid-tied SSES is somewhat reduced (17%) by the addition of bidirectional metering and the use of the energy rebate tariffs already in place within many parts of South Africa. The effect would be larger if the rebate value, presently 31% of the standard tariff and 19% of the higher tariff, were to be more generous.

Levelised Cost of Driving

Use Cases 4 and 5 cover the replacement of the household's ICE with a BEV with or without V2G respectively. Despite the higher capital cost of the BEV, the reduced fuel and maintenance costs make both uses cases lower cost in terms of LCOD. Although not shown in Table 3, the AW value for an option in which there is no SSES and the BEV is recharged directly from the grid at the lower tariff rate is in fact the lowest AW option, giving a value of ZAR 120,766. (The analogous value at the higher Eskom tariff is ZAR 127,015.)

The addition of V2G does mitigate the higher BEV cost, as may be expected, and the AW of Use Case 5 (SESS/BEV/V2G) is almost identical to the base case (Unit Case 1). The similarity is a recent phenomenon; studies earlier than 2020 indicate that BEVs are still expensive relative to the ICE for small households. However, the entry of lower cost vehicles and improvements in V2G integration have improved the techno-economics and BEV ownership and the LCOD values as calculated in this study are not dissimilar to other values already reported in the literature [33].

In summary, BEVs which are V2G enabled have a dual benefit of improving the economics of SSES and BEV ownership, to the extent that these integrated systems are now comparable in cost, ignoring any consideration of carbon emissions and potential carbon tax) to the option of ICE with grid-based electricity supply.

Discussion

V2G offers several major benefits for future energy systems. It can help increase energy system resilience by reducing reliance on centralised energy generation based on traditional large-scale power plants, it can smooth energy demand, it can promote clean energy usage by harnessing the SSES capacity of home users, and it can subsidise the cost of BEV ownership.

A significant contributor to the high LCOE of SSES is the low consumption of available solar energy. One possible solution to this problem might be to increase the available battery storage, enabling greater energy collection during the day and lower dependence on grid-based electricity. However, this is shown not to be the case. Using the model, it is possible to consider the impact of different battery sizes on two important parameters in SSES, namely the fraction of demand served (FDS) and LCOE. The results are shown in Figure 3, from which it is concluded that the 10 kWh battery, as used in this study, is already close to the optimal capacity. Lower capacity rapidly reduces FDS and increases LCOE, whereas larger capacities only marginally increase FDS but quickly increase LCOE.

The sizing of battery energy storage systems is a key topic in the renewable energy literature, and these results are supported by other studies [40,41]. Meeting 100% FDS would require a large and costly battery due to the extreme variability of solar irradiance and hence solar energy, together with unpredictable variations in household energy demand linked to weather and equipment failure (such as a solar geyser). Winter is a particularly vulnerable and intermittent period since the low temperatures increase the demand for electrical space heating and cloudy, wet conditions decrease the available solar energy. Grid usage at this time is almost inevitable and extensive.

The empirical rule for optimal sizing is that the battery capacity should be sufficient to meet an FDS value of 80% to 85%. In other words, on the basis that the annual household electricity demand is about 16.5 kWh/day, as is the case in this study, a usable battery capacity of 80% of the nameplate value, a FDS of 80%, a night-to-day usage split of 1:1 and a net solar panel efficiency of 8.5%, results in a system specification of a peak panel capacity at 6.5 kW and battery capacity of 8/10 kWh.

V2G offers an alternative approach. By ‘selling’ SSES energy to the vehicle, and reducing refuelling costs which would otherwise be incurred, the overall LCOE is reduced. Such as strategy has been demonstrated with Use Case 5, which showed that the energy storage capability of the BEV can be used to increase the overall utilisation of energy availability in the SSES without adversely affecting the utility of either component of the household infrastructure.

As already mentioned, there are multiple challenges to the adoption of V2G, the most important of which is consumer and motor manufacturer resistance arising from the additional cycling of the batteries and associated components, leading to the accelerated depreciation

of these assets, and, of course, additional costs. There are already some solutions to this problem, such as lower battery costs, selection of batteries appropriate to V2G and state of charge management systems [42]. Clearly, battery ageing over time, known as calendar ageing, is unavoidable. Cycle ageing, however, is a function of the depth and number of charge/discharge cycles and can be managed [43]. From the perspective of the vehicle owner, the 20% to 30% reduction in battery lifetime over the duration of ownership needs to be counterbalanced by earnings from the grid operator.

Given that there is little incentive for the vehicle manufacturers to develop these protocols and systems, since V2G is an 'off-label' use of their products, V2G will only proceed if governments, through clear legislative frameworks, drive public interest research to ensure consumer protection and awareness, robust cybersecurity and energy market participation [1],.

Conclusion

Prior studies have reported that V2G technology holds immense potential for revolutionizing energy management and transportation, reducing energy and transport inequalities and accelerating the attainment of Net Zero [3]. However, many of these articles are not supported by the analysis of empirical data allowing for a direct, quantitative comparison of the conventional ICE/grid connection vs. V2G. In this study, we have completed such as analysis. Real-time data, collected from a single SSES, has been used as the input to a model of these systems, allowing for the comparison of four different use cases, including V2G, to the conventional configuration. The analysis shows SSES/BEV combinations are more expensive in all the five use cases, apart from V2G.

Despite the advantages of V2G in a sustainable energy future, its widespread adoption faces several challenges which must be addressed through collaboration between industry stakeholders, policymakers, regulators. In terms of further work, improvements to battery cycle life are necessary, and further research is required to assess a more diverse range of battery materials.

[**Figures/Tables provided in the page below the references**]

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Figures and Tables

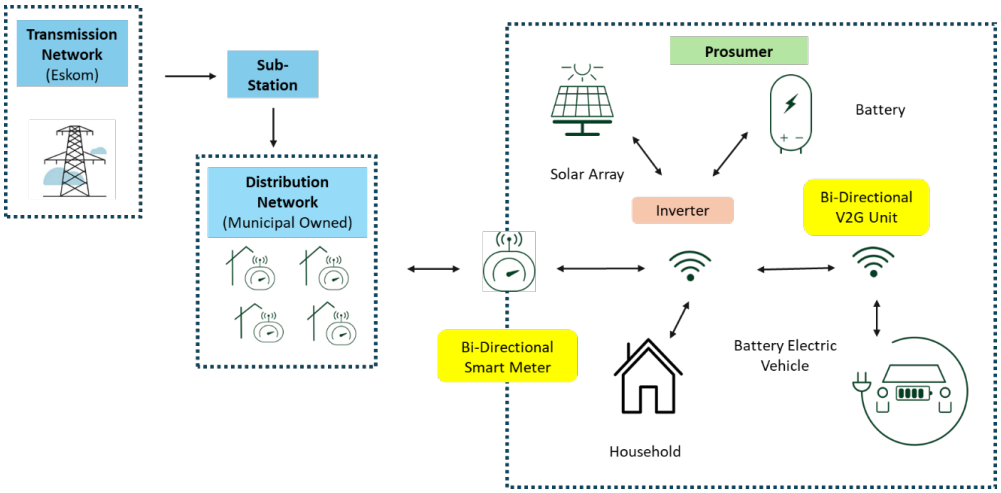

Figure 1. Architecture of V2G as modelled in this study

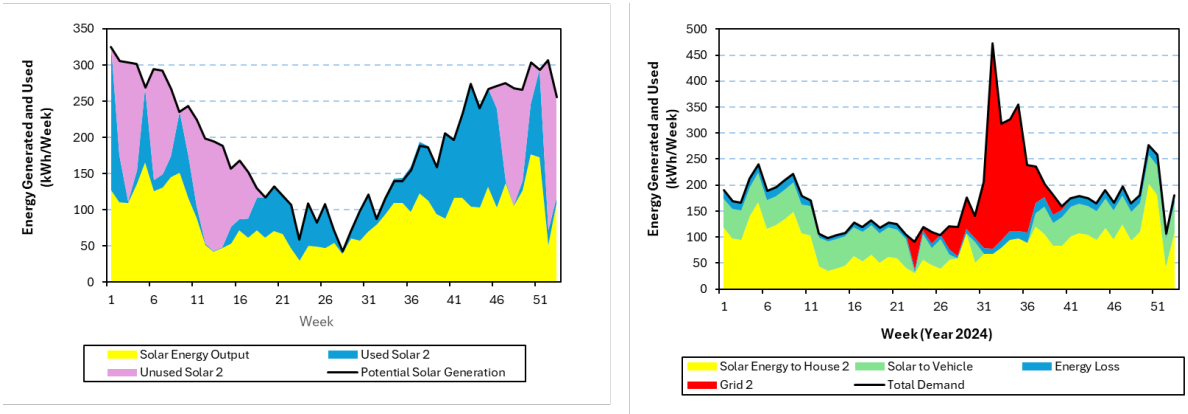

Figure 2. Energy source and demand for V2G

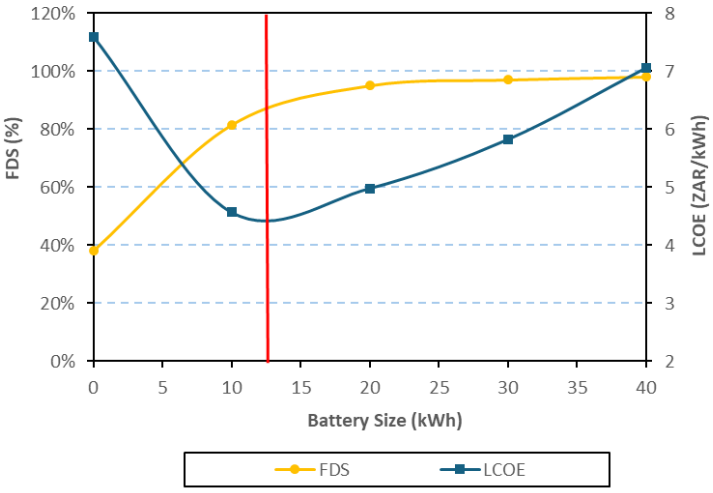

Figure 3. Impact of battery size on LCOE and FDS

Table 1. Outline of the five use cases

Use Case	Description	Type and Size of System Components			
		Solar PV	Inverter	Battery	Vehicle
1	Grid-connected home only (no solar) and ICE vehicle	N/A	N/A	N/A	ICE Sedan 1600
2	Grid-connected with SSES but no rebate on excess energy and ICE vehicle	6.54 kW	10 kW	10/8 kWh	ICE Sedan 1600
3	Grid-tied with SSES and rebate and ICE vehicle	6.54 kW	10 kW	10/8 kWh	ICE Sedan 1600
4	Grid-connected with SSES and BEV (V2H)	6.54 kW	10 kW	10/8 kWh	BEV Sedan 150 kW
5	Grid-tied with SSES and BEV (V2X)	6.54 kW	10 kW	10/8 kWh	BEV Sedan 150 kW

Table 2. System specifications for the five use cases

System Component	Use Case 1	Use Cases 1, 2 and 3	Use Cases 4 and 5
Solar Panels	Not applicable	Not applicable	12 x Canadian Solar HiKu6 Mono PERC each of 545W (fixed mounting)
Vehicle	ICE Sedan 1600 (7.2 l/100 km)	ICE Sedan 1600 (7.2 l/100 km)	BEV Sedan (160 Wh/km and 60.5 kWh battery storage)
Home Energy Use	Profile of annual energy use as per Walwyn[28]		
Distance Travelled	For all use cases it is assumed that the vehicle will used twice per day, each journey being 25 km, in the morning between 07h00 to 08h00 and in the late afternoon between 16h00 to 17h00.		
Battery	Not applicable	Not applicable	Freedom Won LiTE Home 10/8, Max Power 10 kW, Energy 8 kWh @ 80% Depth of Discharge
Inverter	Not applicable	450V, 100A max Victron MPPT RS 450/100 48V	
Bidirectional Meter	Not applicable	Only use cases 3 and 5; standard bidirectional meter approved by the City of Cape Town	

Source: This study, manufacturers' brochures and TechCentral[38]

Table 3. LCOD and LCOE results for all use cases

Case	Vehicle		Household Electricity		Total AW (ZAR)
	LCOD (ZAR/km)	AW (ZAR)	Net LCOE (ZAR/kWh)	AW (ZAR)	
1	6.17	112,707	2.94	17,975	130,682
2	6.17	112,707	5.30	31,819	144,526
3	6.17	112,707	4.43	26,625	139,333
4	5.76	105,097	3.42	30,566	135,663
5	5.72	104,356	3.17	28,299	132,655

Supplementary Material
Financial Assumptions

Input Variable	Units	Value	
		SSES	BEV
Discount Rate	%	8.50%	
Project Lifetime	years	20	10
Maintenance Costs	% of capital	0.60%	2.40%
Network Capacity Charge	ZAR/year	2.67	
Energy Rebate Rate	ZAR/kWh	0.87	
Unit Cost Electricity (<600 kWh/month)	ZAR/kWh	2.82	
Unit Cost Electricity (> 600 kWh/month)	ZAR/kWh	4.54	
Photovoltaic Panels (per panel)	ZAR	27,500	
Lithium Battery (per 10 kWh)	ZAR	53,000	
Inverter	ZAR	21,000	
Maximum power point tracking (MPPT)	ZAR	52,500	
Balance of Plant Cost	ZAR	43,000	
Installation SSES	ZAR	18,000	
Total Capital Cost	ZAR	215,000	539,000

Source:

Costs of SSES: Walwyn D. An Alternative to Higher Energy Tariffs; Extracting Unused Capacity from Small-Scale Embedded Solar. S Afr J Sci. 2025; under review:1-14.

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