Environmental impacts of electric vehicles in South Africa

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Electric vehicles have been seen by some policymakers as a tool to target reductions in greenhouse gas emissions.[1,2] Some researchers have shown that the full environmental impact of electric vehicles depends very much on the cleanliness of the electricity grid.[3] In countries such as the USA and China, where coal-fired power plants still play a very important role in electricity generation, the environmental impact of electric vehicles is equivalent to, or even higher than that of cars running on internal combustion engines.[4,5] In this study, the environmental impacts of electric vehicles in South Africa were investigated. We found that, as the bulk of South Africa's electricity is generated from relatively low-quality coal and the advanced exhaust clean up technologies are not implemented in the current coal-fired power plants, the use of electric vehicles in South Africa would not help to cut greenhouse gas emissions now (2010) or in the future (in 2030 using the IRP 2010 Revision 2, policy-adjusted IRP scenario), and actually would lead to higher SO_x and NO_x emissions.

Introduction

Electric vehicles were invented in the 19th century but were replaced by automobiles with internal combustion engines (ICEs) in the early 20th century. However, electric vehicles have drawn more and more research and commercial interest during the last few decades because of the increased concern about the environmental impact of the petroleum-based transportation infrastructure. There have also been concerns about the security of the oil supply, especially after the oil price hike in mid-2008. US President Barack Obama announced in August 2009 a USD 2.4 billion investment to drive the development of the next generation of electric vehicles in the USA. The aims of the investment are also to support the growth of domestic jobs, reduce the use of petroleum, reduce greenhouse gas (GHG) emissions and advance the USA's economic recovery, national energy security and environmental stability.[1] The Department of Trade and Industry in South Africa also announced in early 2010, in its 2010–2013 Industrial Policy Action Plan, a plan to commercialise South Africa's electric vehicles.[2]

The major advantages of electric vehicles are that they can utilise almost all the kinds of energy resources that can be used to generate electricity, thereby reducing the dependence of transportation on the volatile petroleum market; they can take advantage of the development of renewable energy for electricity generation; and there are no emissions at the end use, which helps to reduce pollution in urban areas.

Although electric vehicles are generally considered to be clean, the full environmental implication of electric vehicles depends very much on the cleanliness of the electricity grid. Nicolay et al.[3] pointed out in 2000 that the results of a life cycle assessment on electric vehicles depend strongly on the efficiency of the energy supply chains as most of the pollutants considered in the study (CO_2, NO_x, SO_x, etc.) are directly linked to combustion. A report released in October 2009 by the National Research Council in the USA reported that when the damage and impacts of the whole life cycle were considered, the aggregate impacts depended on the grid; in that case the impacts of all electric vehicles became comparable to, or somewhat higher than, those from petrol in the USA, where coal and natural gas fired power plants account for the majority of total generation.[4]

Huo et al.[5] studied the environmental implications of electric vehicles in China, where improved but still low efficiency and heavily polluting coal-fired power plants make up more than 80% of the total generation. They concluded that, in 2008, electric vehicles in China did not promise much benefit in reducing CO_2 emissions, compared with conventional petrol vehicles and petrol hybrids. A greater CO_2 reduction could be expected if coal combustion efficiency improved and the share of the non-fossil electricity increased significantly.[5] The study also revealed that electric vehicles could increase SO_2 emissions by three to ten times and also double NO_x emissions compared with petrol vehicles, if the electric vehicles were charged using the current grid in China. These studies raised concerns about the timing of rolling out electric vehicles in some states. We studied the environmental implications of electric vehicles in South Africa now (2010) and in the future (2030).

Generation mix

There are arguments in the USA that the increasing penetration of electric vehicles may require additional and new power capacity. Therefore the energy and environmental impacts of electric vehicles should be evaluated based on the marginal generation mix.[6,7,8] This approach is reasonable in the USA as the electricity consumption there has been stabilised in the last decade[9] and the new capacity would be mainly for electric vehicles. This situation does not apply to South Africa or to other fast developing countries where electric vehicles will be only one of the factors in increasing electricity consumption.[5]

There has been on average a 3% electricity consumption growth rate over a 20-year period in South Africa; 20 GW of additional generation capacity is required by 2020 and up to 40 GW by 2030, on top of the current net installed generation capacity and contracted imported generation amounts of 43.5 GW.[10] As Eskom's older coal-fired power stations will probably start to be decommissioned from 2023 onwards, a new capacity of 50 GW by 2030 is estimated by Eskom. The Council for Scientific and Industrial Research forecast that the electricity demand in South Africa in 2030 will be 40% to 60% higher than the electricity demand in 2009; Eskom's System Operations and Planning Division model forecast even higher demand.[11] Electricity consumption for electric vehicles was not considered in either forecast.

As stated in the Eskom 2010 Annual Report, coal-fired power stations contributed 92.8% of the total of 232 812 GWh electricity generation by Eskom in 2009/2010, balanced by 5.5% from nuclear, 1.2% from pumped storage and other, 0.5% from renewable energy and only 0.02% from gas.[10] The Integrated Resource Plan (IRP 1) published in January 2010 projected 10 000 GWh (approximately 4% of the energy mix) of renewable energy by 2013.[12] This projection indicates an increase of renewable energy in the future, but the number is still insignificant as the majority of the newly installed capacity is still from coal.

The Integrated Resource Plan (IRP 2010 Revision 2) summarises the existing South African generation capacity in its Appendix D.[11] It states that, amongst all the power plants operated by Eskom and others, coal-fired power plants contribute 35.5 GW generation capacity, nuclear contributes 1.8 GW and hydropower 2.1 GW (including 1.5 GW from Cahora Bassa) to base load generation. Pump storage contributes 1.58 GW for peaking supplies together with 2.4 GW from gas turbines.[11] There is a further 0.5 GW generation capacity from various limited energy plants using various resources.

The IRP 2010 Revision 2, which was promulgated in May 2010, also draws a picture of the generation mix in the future.[11] The 'revised balanced scenario' was considered to represent a fair and acceptable balance when the draft report was released in October 2010,[11] considering the divergence in stakeholder expectations and key constraints and risks.[11] A 'policy-adjusted IRP' was proposed in the final report released in March 2011.[11] In the policy-adjusted IRP scenario, 54.7 GW generation capacity will be built between 2010 and 2030, with 10.9 GW capacity decommissioned. This build will increase the current total generation capacity to 89.5 GW to cope with the peak demand forecast of 67.8 GW in 2030. Renewable power generation technology will dominate the newly built generation capacity (including the committed new builds) with a total of 18.8 GW, followed by coal-fired power plant's 16.4 GW, nuclear's 9.6 GW, peak open-cycle gas turbine plant's 4.9 GW and closed-cycle gas turbine plant's 2.4 GW, as well as 2.6 GW of imported hydropower. By 2030, 10.9 GW coal generation capacities will be decommissioned. The current (2010) generation mix and that projected for 2030 (according to the policy-adjusted IRP) are summarised in Table 1.

There is transmission and distribution loss in the grid. The actual loss as stated in the Eskom 2010 Annual Report[10] was 8.45% in 2010, which includes a total distribution loss

TABLE 1: Generation capacity and energy share in South Africa in 2010 and in 2030[a].

Fuel type	Fuel subtype	Generation capacity (GW)		Energy share (%)	
		2010	2030	2010	2030
Coal	-	35.5	41.1	90.0	65.5
	Current (includes return to service)	35.5	26.1	90.0	41.6[b]
	New PF	-	11.0	-	17.5[b]
	New FBC	-	1.75	-	2.8[b]
	New PF + FGD	-	2.25	-	3.6[b]
Nuclear	-	1.8	11.4	5.0	20.0
Pump storage	-	1.6	2.9	-	-
Gas-CCGT	-	0.0	2.4	0.0	0.8
Peak-OCGT	-	2.4	7.3	< 0.1	0.2
Hydropower	-	2.1	4.8	5.0	6.0
Renewables	-	0.0	18.8	0.0	7.5
Others	-	0.5	0.9	< 0.1	< 0.1
TOTAL	**-**	**43.9**	**89.5**	**100.0**	**100.0**

PF, pulverised fuel; FBC, fluidised bed combustion; FGD, flue gas desulphurisation; OCGT, open-cycle gas turbine; CCGT, closed-cycle gas turbine.
[a], Based on the policy-adjusted integrated resource plan (IRP) from IRP 2010 Revision 2.[11]
[b], Estimated under the assumption that all coal-fired power plants contribute the same online time.

of 5.87% and a total transmission loss of 3.27%. This loss, as claimed by Eskom, is within the benchmark parameters of 5.60% to 12.07% and in the first quartile of the top performing distribution utilities in terms of total energy losses. Improvement is therefore not forecast in the loss management. The lower benchmark of 5.60% loss is estimated for 2030.

The Eskom 2010 Annual Report states that for every kWh generated, CO_2 emissions are 0.98 kg, particulate emissions 0.39 g, SO_2 emissions 8.10 g and NO_x (as NO_2) emissions are 4.17 g.[10] These numbers are very high compared to European countries, Australia and the USA, as stated in the annual report, but agree with the findings of von Blottnitz[13] that the South African power industry emits more nitrous oxide, sulphur oxide and particulates than are emitted by electricity generators in any of the 15 European countries studied. According to von Blottnitz[13], these higher emissions are because of (1) the comparatively high specific emissions from coal-fired power plants (with South African stations performing at the worst level relative to most of Europe, alongside the Spanish, Greek and Hungarian industries), and (2) the comparatively very extensive use of coal for electricity generation in South Africa.[13]

There has not been any major plan from Eskom to significantly improve the efficiency and pollution control of current coal-fired power plants. New technologies do exist to improve the emissions and the energy efficiencies from coal-fired power plants and have been used worldwide. The IRP 2010 input parameters published by the Department of Energy in South Africa for various technologies have been investigated and are listed in Table 2, together with the current (2010) generation mix and that projected for 2030 (according to the policy-adjusted IRP).

Liquid fuel

Unlike in most other countries where crude oil is the only source for petrol and diesel, a significant amount of liquid fuel consumed in South Africa is made from coal and natural gas by way of coal-to-liquid and gas-to-liquid processes, from which Sasol and PetroSA have contributed close to 36% of the total liquid fuel market.[14] There is no report available for South Africa that analyses the life cycle emissions of synthetic liquid fuel, which are very different from those of conventional fuel. Synthetic liquid fuel produced via the Fischer–Tropsch process has a very low sulphur content (less than five parts per million), which is lower than the sulphur content requirement in the current fuel quality standards.[15,16] When carbon capture and sequestration technology is not applied, the life cycle carbon emission from synthetic fuel is higher than that of conventional liquid fuel.[17] The NO_x and particulate emissions from an engine using synthetic fuel are close to, or lower than, those of conventional fuel.[18,19]

Because of a lack of detail regarding the life cycle assessment of synthetic liquid fuels, as well as to simplify the calculation, we assumed in this study that the introduction of electric vehicles in South Africa will initially replace only the market share of the imported conventional liquid fuel that is made from crude oil. Emissions from synthetic liquid fuel are therefore not included in this study.

The environmental standards for liquid fuel quality in South Africa are low. The current refineries in South Africa produce petrol and diesel based on the dated Euro III specifications, which are reflected in SANS 1598:2006 for petrol and SANS 342:2006 for diesel. The sulphur content of petrol and standard diesel is set at 500 mg/kg. The sulphur content of high-quality diesel is set at 50 mg/kg, but this diesel is available in only some parts of the country. There has been commitment from the South African Petroleum Industry Association to progress towards Euro IV-compliant fuel, which has a sulphur content of 50 mg/kg,[20] or even Euro V-compliant fuel, which has a sulphur content of 10 mg/kg.[21] It is presumed in this study that the sulphur content of petrol and diesel in South Africa in 2030 will meet the Euro V-compliant standard, which is less than 10 mg/kg.

The emissions from light passenger vehicles in South Africa are regulated in SANS 20083:2007, which is equivalent to the Euro III standards.[22] It was presumed in this study that the Euro VI-compliant[23] emission standards will apply in South Africa in 2030. The relevant emission limits are listed in Table 3.

There is no report on the overall petroleum refining and distribution efficiency in South Africa. A study conducted

TABLE 2: Generation life cycle cost of various generation technologies compared with the current and future (2030) generation mix.[11]

Technology	Generation life cycle cost (g/kWh)			
	CO_2	SO_x	NO_x	Particulate matter
Generation mix 2010[10]	980	8.10	4.17	0.39
Pulverised coal[11]	924	8.93	2.26	0.12
Pulverised coal with FGD	936	0.45	2.30	0.13
Fluidised bed with FGD	977	0.19	0.20	0.09
OCGT	622	0.00	0.28	0.00
CCGT	376	0.00	0.29	0.00
Nuclear	0	0.00	0.00	0.00
Renewable[a]	0	0.00	0.00	0.00
Generation mix in 2030 (based on policy-adjusted integrated resource plan)	630	4.95	2.22	0.19

FGD, flue gas desulphurisation; OCGT, open-cycle gas turbine; CCGT, closed-cycle gas turbine.

[a], There are emissions from a renewable power plant, especially when biomass is used. However, renewable power plants were not considered in this calculation as biomass does not contribute a significant amount of generation capacity according to the Integrated Resource Plan 2010 Revision 2 and the exact contribution is still unclear. Emissions from a co-generation plant were also set to 0 to simplify the calculation.

TABLE 3: Emission standards for light passenger cars.

Emission standards	Vehicle type			
	Petrol		Diesel	
	NO_x (g/km)	Particulate matter (g/km)	NO_x (g/km)	Particulate matter (g/km)
Current (Euro III)	0.15	-	0.50	0.0500
2030 (Euro VI)	0.06	-/0.005[a]	0.08	0.0025

[a], Applies only to vehicles with direct injection engines.

in Europe reports an energy consumption of 0.155 MJ/MJ with 14 g CO_2eq/MJ emissions for diesel fuel and an energy consumption of 0.125 MJ/MJ with 12 g CO_2eq/MJ emissions for petrol.[17] Crude oil refining accounts for most of the energy costs and the CO_2 emissions. These values were adopted in our calculations for 2010. A 20% efficiency increase was estimated for 2030, which gives an amount of 11 g CO_2eq/MJ for diesel. These emission estimations are obviously different from that in South Africa and our calculations should be reconsidered when the local value is available. The SO_x, NO_x and particulate emissions during the refining and distribution of liquid fuel are unknown and were not considered in this study.

Fuel efficiency

The National Association of Automobile Manufacturers of South Africa provides the fuel efficiency and carbon emission data of all the cars in the South African market on its website.[24] The fuel consumption for 1.6 L – 1.8 L petrol-engine light passenger cars is close to 7 L/100 km, with CO_2 emissions close to 165 g/km. The fuel consumption for 1.6 L – 1.8 L diesel-engine light passenger cars is close to 5.2 L/100 km, with CO_2 emissions close to 135 g/km. The fuel efficiency and CO_2 emission values used in this study were therefore, respectively, 7 L/100 km and 165 g/km for petrol engines and 5.2 L/100 km and 135 g/km for diesel engines. The only hybrid petrol passenger car in South Africa is the Toyota Prius Hybrid. The fuel efficiency of the Prius is 4.1 L/100 km, with CO_2 emissions of 94 g/km.[24] The Prius has a special design for better fuel efficiency and therefore cannot be used here for comparison.

There is no report available on the on-road efficiency of other petrol hybrid electric vehicles and electric vehicles in South Africa. The first South African made electric vehicle, Joule, is expected to be available in 2013.[25] The Joule is a light passenger car with five seats and a 230 km to 300 km range. It can be regarded as comparable to the 1.6 L – 1.8 L conventional fuel light passenger cars, but the energy consumption of the Joule has not yet been released on its manufacturer's website. The ratios of the fuel efficiency values of hybrid electric vehicles, electric vehicles and conventional vehicles in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model[26] were adopted on the basis of the same class of vehicle, as well as the same driving conditions.

At the moment, there are no regulations for CO_2 emissions in South Africa, and therefore no regulations for the fuel efficiencies of vehicles. The European Union had a voluntary agreement with the European Automobile Manufacturers Association, which was to achieve a fleet average for CO_2 emissions of 140 g/km (equivalent to 5.8 L/100 km for petrol) in 2008 for new passenger cars. This target was not achieved. The ultimate target is now 130 g/km CO_2 emissions for all new passenger cars by 2015. The European Union is pushing for a new target of 95 g/km for a new car fleet average in 2020.[27] In this study, we assumed that by 2030, petrol-engine light passenger cars in South Africa will have achieved the CO_2 emission target of 130 g/km (5.6 L/100 km for petrol). The fuel efficiencies of the diesel-engine vehicles, petrol hybrid, and electric vehicles for 2030 were adjusted according to the fuel efficiency ratio in 2010.

The rated fuel consumptions of conventional petrol internal combustion engine vehicles (ICEVs), diesel ICEVs, petrol hybrid electric vehicles and electric vehicles are listed in Table 4.

Comparison

The life cycle CO_2, SO_x, NO_x and particulate matter emissions (PM) for vehicles are listed in Table 5. The analysis from GREET indicates that more than 97% of the SO_x emissions for electric vehicles are from electricity generation. Only SO_x emissions from electricity generation were considered in our calculations and only NO_x and PM emissions from electricity generation were considered for electric vehicle pollution in this calculation. The CO_2 equivalent (CO_2eq) was also listed. The CO_2eq is calculated as the CO_2 emission plus the CO_2eq of NO_x. The global warming potential of NO_x is 298, which is used in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change.[28]

CO_2 emissions

It has been shown that when the current grid in South Africa is used to charge electric vehicles, there is an increase in CO_2 emissions of between 17% and 64%. The actual increase in CO_2 emissions by electric vehicles might be less than this amount because there are many inefficient cars on the roads in South Africa. Petrol hybrid vehicles perform the best with respect to CO_2 emissions, with a 30% reduction in CO_2 emissions; the adoption of petrol hybrids is therefore the direction that should be encouraged in the near future.

With the application of advanced electricity generating technologies and fewer coal-fired power plants in the

TABLE 4: Assumptions of fuel efficiency and CO_2 emissions of light passenger vehicles.

Vehicle type	Fuel efficiency (L/100 km)		CO_2 emissions (g/km)	
	2010	2030	2010	2030
Petrol ICEVs	7.0	5.5	165	130
Diesel ICEVs	5.2	4.1	135	106
Petrol hybrid	5.0	3.9	118	93
Electric vehicle (kWh)	21.0[a]	16.0[a]	-	-

ICEV, internal combustion engine vehicle.
[a], Battery recharge loss included.

TABLE 5: Life cycle CO_2, SO_x, NO_x and particulate matter emissions in 2010 and 2030.

Vehicle type	Year	Emissions (g/km)				
		CO_2	SO_x	NO_x	Particulate matter	CO_{2eq}
Petrol ICEV	2010	192	0.0520	0.150	-	237
	2030	147	0.0008	0.060	-/0.0005[a]	165
Diesel ICEV	2010	161	0.0430	0.500	0.0500	310
	2030	123	0.0007	0.080	0.0025	147
Petrol hybrid	2010	137	0.0380	0.150	-	182
	2030	104	0.0006	0.060	-	122
Electric vehicle	2010	225	1.8580	0.960	0.0890	511
	2030	101	0.7930	0.335	0.0300	207

ICEV, internal combustion engine vehicle.

[a], Applies only to vehicles with direct injection engines.

generation mix, the CO_2 emissions from electric vehicles can be reduced significantly from the current level. In the case of the proposed policy-adjusted IRP in the IRP 2010 Revision 2, electric vehicles will be the low carbon emission option in 2030, producing only 69% of the CO_2 emissions of a petrol ICEV and 97% of the CO_2 emissions of a petrol hybrid electric vehicle per kilometre travelled.

SO_x emissions

When electric vehicles are charged with the current grid in South Africa, 35 to 50 times more SO_x (1.86 g/km) is emitted than from ICEVs (0.04 g/km – 0.05 g/km). SO_x pollution, which leads to acid rain, is a more serious environmental problem than GHG emissions as it affects plant ecosystems, including agricultural ecosystems, in a very short time. With the application of advanced technologies, as well as a cleaner grid, the life cycle SO_x emissions from electric vehicles can be reduced to 0.793 g/km. Such a reduction still makes the SO_x emissions from electric vehicles more than 10 times higher than the current SO_x emissions from the ICEVs, and the emissions more than 1000 times higher than those from the ICEVs in 2030 (0.0006 g/km – 0.0008 g/km) if the new low sulphur fuel standards are implemented.

NO_x emissions

When electric vehicles are charged in the current grid in South Africa, the NO_x emissions are two to six times higher (0.96 g/km) than those of the ICEVs (0.15 g/km – 0.50 g/km). As the grid becomes cleaner, the NO_x emissions can be reduced to 0.34 g/km if the policy-adjusted IRP scenario proposed in the IRP 2010 Revision 2 is implemented. This number is in the order of the NO_x emissions from the ICEVs in 2010 but is still four to six times higher than those of the ICEVs in 2030 when new emission standards are applied.

Particulate matter emissions

There are no PM emissions from petrol ICEVs and petrol hybrid electric vehicles unless direct injection engines are used. The petrol vehicles using direct injection engines are just entering the South African market and were not considered in this calculation for current (2010) petrol ICEVs emissions. If electric vehicles are charged from the current grid in South Africa, the PM emissions are double those of diesel ICEVs. In 2030, the PM emissions from an electric vehicle are 12 times higher than those of a diesel ICEV, and 6 times higher than those of a direct injection petrol ICEV, although a two-thirds emission cut can be achieved from the grid compared with that of 2010. It can be argued that PM emissions are not as serious as the other pollutants, as the PM emissions from the power plants are normally located in remote areas. The effects of the PM emissions in those areas cannot be compared directly with the PM emissions from the diesel ICEVs, which are located in the city, but there are large settlements around coal fields and coal-fired power plants in South Africa; these 'remote' areas are actually peri-urban. The PM emissions, together with the NO_x and SO_x emissions, will result in smog, which is already a serious problem in those areas.

Greenhouse gas emissions

Because of the very high greenhouse potential of NO_x and the high emission level of NO_x from electric vehicles, the total life cycle GHG emission measure of CO_2eq of electric vehicles (511 g/km) is 65% to 115% higher than that of ICEVs when electric vehicles are charged with the current grid. A 60% reduction (to 207 g/km) in the total GHG emission is proposed in the policy-adjusted IRP scenario in 2030. This value is in the order of the total GHG emission of hybrid electric vehicles in 2010 (182 g/km to 310 g/km), but is 25% higher than petrol ICEVs, 41% higher than diesel ICEVs, and 70% higher than hybrid electric vehicles in 2030.

Conclusions

The major advantage of electric vehicles is that there is no emission at the user end, which will help to improve the air quality of urban areas. The pollutants from ICEVs and hybrid electric vehicles that affect the air quality are CO, hydrocarbons and PMs. The emissions of the CO and hydrocarbons from electric vehicles were not studied here as the emissions of such pollutants at the user end are zero. PMs may only affect the areas surrounding coal-fired power plants, but these areas are normally peri-urban; the PM pollution, together with SO_x and NO_x emissions, will result in smog in these areas.

In terms of CO_2, SO_x and NO_x emissions, whose effects are not limited to the point of pollution, the environmental benefits from electric vehicles are very limited in the current situation. The worst case scenario is that 35 to 50 times more SO_x will be emitted when conventional vehicles are replaced with electric vehicles in the current grid. The CO_2 emissions from electric vehicles in the current grid are higher than those of vehicles using conventional liquid fuel. NO_x emissions will be at least double those of ICEVs and hybrid electric vehicles. The total GHG emission is actually greater from electric vehicles.

As the grid is becoming cleaner, thanks to the implementation of advanced coal-fired power plant technology as well as renewable energy, these emissions can be cut significantly in 2030. Electric vehicles will be a cleaner option when only CO_2 emissions need to be considered in 2030, with similar performances from petrol hybrid electric vehicles. When switching to electric vehicles from ICEVs, a reduction in CO_2 emissions of 18% to 31% can be achieved per kilometre travelled. In the case of NO_x, the life cycle NO_x emissions from electric vehicles will still be four to six times higher than those from vehicles using conventional liquid fuel. As the reduction in NO_x emissions is not significant enough, electric vehicles are still the worst option when one considers the total GHG emissions. The worst case is that of SO_x: although there is a projected 43% reduction in SO_x emissions from the grid in 2030 compared to in 2010, the life cycle SO_x emission from electric vehicles will be more than 1000 times higher than those from ICEVs and hybrid electric vehicles in 2030.

Implementing electric vehicles in South Africa does not help to cut total GHG emissions, now (2010) or in the foreseeable future (2030), and would lead indirectly to higher SO_x and NO_x emissions. If electric vehicles are to play an important role on South Africa's roads, new technologies have to be investigated and implemented to lower the SO_x and NO_x emissions for electricity generation further, in order to make electric vehicle emissions comparable to those of ICEVs and hybrid electric vehicles.

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Competing interests

We declare that we have no financial or personal relationships which may have inappropriately influenced us in writing this article.

Authors' contributions

Dr Liu was the main investigator and wrote the manuscript. Prof. Hildebrandt and Prof. Glasser made conceptual contributions and reviewed the manuscript.

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