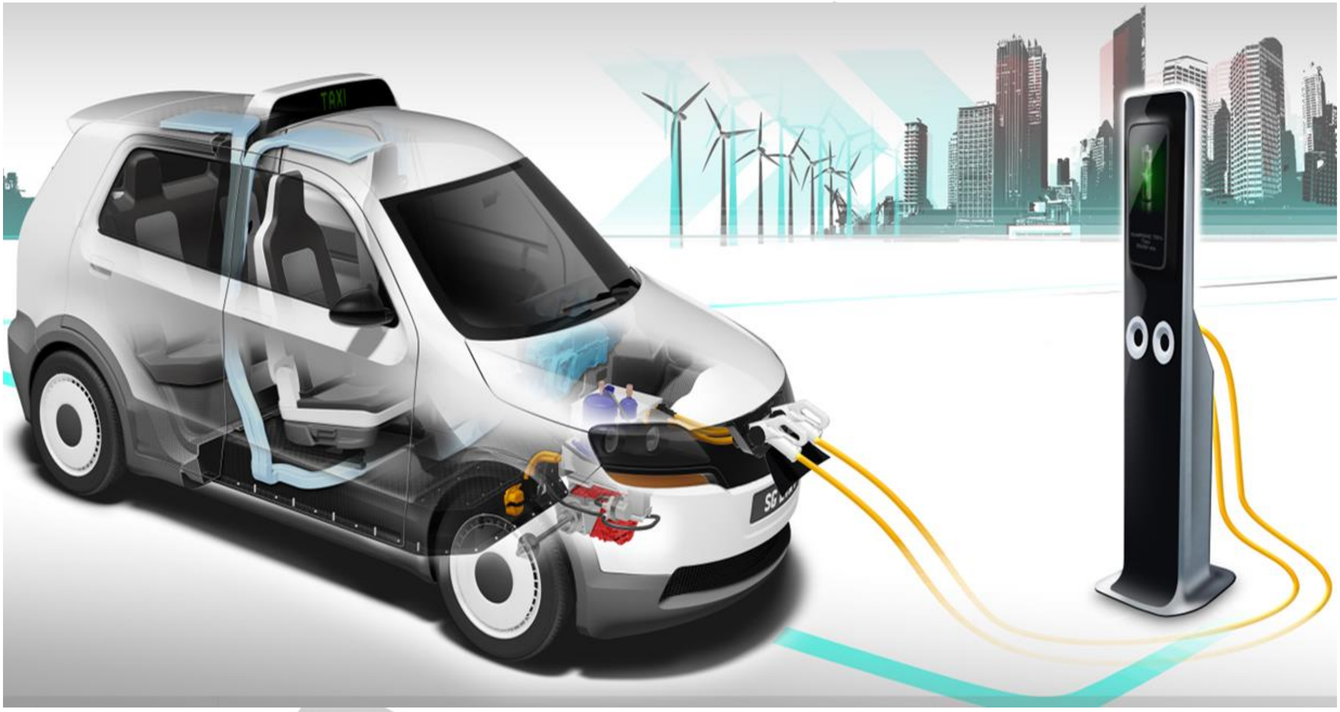
Electrification of Road Transport in Singapore and its Integration into the Power System

Tobias Massier*[a], Dante Recalde[a], Reinhard Sellmair[a], Marc Gallet[a], Thomas Hamacher[b]



This is the peer reviewed version of the following article: T. Massier, D. F. Recalde Melo, R. Sellmair, M. Gallet, and T. Hamacher, "Electrification of road transport in Singapore and its integration into the power system," Energy Technology, vol. 6, no. 1, John Wiley & Sons VCH, Jan. 2018, pp. 21–32, which has been published in final form at https://doi.org/10.1002/ente.201700652. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

Abstract: Being a small well-organized city state, Singapore appears to be an ideal place to establish a fully electric road transport system. In order to analyze the challenges and potential of electric mobility (or "electromobility"), TUMCREATE Ltd., a company funded by Singapore's National Research Foundation, was launched in 2011 as "Centre for Electromobility in Megacities". During the first five years, the research at TUMCREATE covered everything "from the molecule to the megacity", i.e., from fundamental research on new materials for energy storage systems to battery cells, battery packs, vehicle technology, in-vehicle electronics to road infrastructure and the power system. One outcome was a prototype for an electric taxi for tropical megacities called EVA with a battery capacity of 50 kWh and fast charging capability of 160 kW. This paper presents a review of past and ongoing activities in the field of integration of electromobility into Singapore's power system. The focus of this paper lies on charging of electric vehicles (EVs). Results show that the integration of EVs into the power system is feasible, leads to lower emissions and can even offer new services and support integration of renewable energies.

1. Introduction

Singapore is a small island city state with a land area of approximately 720 km² and 5.6 million inhabitants.[1] The total number of road vehicles amounts to about one million.[2] The majority of these are private vehicles (approx. 537 000). Commuters are encouraged to take public transport instead of private vehicles.[3] For this reason, high taxes are imposed on private vehicles and drivers have to get the Certificate of Entitlement (COE) first, in order to have the right to drive a car on Singapore's roads. In 2016, the share of total final energy consumption of the transportation sector was approximately 17 %.[4] By 2020, it is expected to contribute to 14.5 % of greenhouse gas (GHG) emissions.[5]

The number of electric and hybrid passenger vehicles globally increased from 350 000 in 2013 to more than two million vehicles at the end of 2016.[6] The increase in the EV population results from a combination of factors: incentive schemes that promote sustainable mobility options, changes in drivers' perspective towards green transportation modes and the constant advancement of lithium-ion and battery technology in general.[7] Countries like Norway, the Netherlands and Sweden lead the way in the number of new registrations of EVs compared to the total vehicle fleet.[6]

In Singapore, electromobility is seen as the key way of achieving the global carbon emission reduction for complying with both 2020 and 2030 goals of the United Nations Framework Convention on Climate Change. The Energy Market Authority (EMA) and the Land Transport Authority (LTA) of Singapore launched an EV test-bed in 2010. A survey revealed that the high purchase cost, concerns over range anxiety and the availability of personal and public charging infrastructure were the main concerns for users that will prevent them from buying an EV.[8] As a second phase of the EV test-bed, the LTA and the Singapore Economic Development Board (EDB) are expecting to introduce a car sharing program which includes up to 1000 EVs and the charging infrastructure required for supporting this fleet. The program is scheduled to start operation in late 2017.[9]

Aside from greenhouse gas emissions, switching to EVs would also reduce emissions of pollutants, heat and noise. It would also lower Singapore's energy demand – particularly of oil – due to the higher efficiency of EVs. However, it would increase electricity demand and consequently demand for natural gas as the major portion of Singapore's electricity supply is covered by gas power plants. Natural gas is mainly imported from Malaysia and Indonesia. As natural gas power plants are rather clean, polluting emissions would decrease (see Section 5). Further emission reduction could be achieved by using solar photovoltaics (PV) which could be installed in Singapore (see Section 2.1).[10]

Further challenges of electromobility include the charging infrastructure and scheduling, and the integration into the power system and energy market. The average daily mileage of private cars is very low and cars are usually not parked at the side of the road, but in car parks. Hence, it is sufficient to equip car parks with charging stations instead of developing an on-the-road charging infrastructure. Due to the low mileage, fast charging is usually not required, such that the impact on the power system would be rather low. Car park operators could act as providers of ancillary services (see Section 4.1). However, electric public transport vehicles such as taxis and buses require fast charging due to their high mileage and low standstill times. This will put additional strain on the grid – particularly the distribution grid – and require measures such as demand response. Vehicle battery constraints have to be observed in order to prevent premature battery degradation.

The integration of EVs into the grid has been discussed in numerous studies – usually for particular places or cities. A first charging optimization method for passenger cars in Singapore was presented in 2007.[11] Recent studies worldwide focus on smart grid applications including demand response and integration of renewable energies.[12-15] The implementation of charging infrastructures for electric vehicles in different parts of the world has been discussed extensively. In Micari[16], vehicle and charging station technology, as well as traffic flow are considered and applied for a road network in Italy. In Awasthi[17] A hybrid optimization algorithm combining heuristics was used for charging infrastructure planning in the

[a] Dr. T. Massier, Dr. D. Recalde, R. Sellmair, M. Gallet
Electrification Suite & Test Lab
TUMCREATE Ltd.
1 CREATE Way, #10-02 CREATE Tower
Singapore 138602
E-mail: tobias.massier@tum-create.edu.sg
[b] Prof. Thomas Hamacher
Chair of Renewable and Sustainable Energy Systems
Technische Universität München
Lichtenbergstr. 4a
D-85748 Garching
Germany

distribution grid. A case study in an Indian city was shown. An approach incorporating load profiles and traffic constraints was presented by Xiang.[18] It was applied on a fictitious network. The case of Singapore is rather unique though, with cars parking almost entirely in car parks and most vehicles usually not leaving the city state during the day.

With decreasing battery costs and sizes, electrifying public road transport – which mainly comprises buses – has become an interesting option as well. With no direct tailpipe emissions, overall better energy efficiency and increased comfort for commuters (due to lower motor noise and fewer motor vibrations), electric buses can solve a number of issues simultaneously.[19] However, battery constraints may result in limitations on the available operation range.[20] Then again, buses run on fixed routes which makes charging scheduling more predictable and planning of a charging infrastructure easier. Various studies[21-23] and field tests[24-27] were performed in recent years and many cities in the world are currently planning to integrate electric buses in pilot phases.[28] However, these studies have mainly been limited to case studies at a limited scale or pilot projects which only covered a few vehicles, a small bus network or a few selected routes from a bigger transit network.

This review summarizes TUMCREATE's research and results in the field of electrification of road transport since 2011. We include both previously published work and recent results. Our research comprises the analysis of the demand of different types of EVs, their impact on the power system and potential contributions towards a smarter grid. Section 2 contains an overview of Singapore's power system and describes the model used throughout the paper. Section 3 covers different aspects of the electrification of private passenger cars, taxis and public buses in Singapore. In Section 4, we discuss several smart grid applications of EVs. Section 5 presents the emission reduction potential of electromobility in Singapore. Section 6 concludes the paper.

Tobias Massier received the Dipl.Ing. (M.Sc.) and Ph.D. degrees in electrical engineering and information technology from the Technical University of Munich (TUM), Germany, in 2002 and 2010, respectively. From 2009 to 2012, he managed the Master Program in Power Engineering at TUM. Since 2013, he has been with TUMCREATE as Principal Investigator of the research group Electrification Suite and Test Lab. His research interests are in transportation electrification and integration, vehicle emissions, and renewable energies.

Dante Recalde received the B.S. and M.S. degrees in electrical engineering from the National Cheng Kung University, Taiwan, in 2010 and 2012, respectively. He obtained his Ph.D. degree from Nanyang Technological University, Singapore in 2017. In 2015, he obtained the best oral presentation by a young engineer award at the International Universities' Power Engineering Conference (UPEC). Currently, he is a research fellow in the Electrification Suite & Test Lab group at TUMCREATE, Singapore. His research interests include renewable energy sources and electric vehicles integration, power system operation and distribution system optimization.

Reinhard Sellmair holds a diploma degree in physics from the Technical University of Munich, Germany. During his diploma thesis he used a socio dynamic approach to analyse under which technical and economic conditions electric taxi can be introduced in Munich. He joined TUMCREATE Ltd. in Singapore as a research associate in 2012. His research focus is optimizing a charging infrastructure for electric taxis.

Marc Gallet completed an international double-degree program in 2013, receiving a Master of Science from Technische Universität München (TUM), Germany and an Engineering Degree from the École Supérieure d'Électricité, France, both in Electrical Engineering and Information Technology. From February 2014 to January 2017 he was a research associate at the Research Center for Energy Economics (FfE e.V.) in Munich, Germany. Since February 2017, he has been working as a research associate in the Electrification Suite and Test Lab (ESTL) at TUMCREATE and pursues his doctoral degree. His research interests include the optimization of the charging infrastructure for electric mobility in the public transport system as well as the integration of renewable energy for sustainable mobility in the future.

Thomas Hamacher studied Physics in Bonn and Aachen and at Columbia University, New York. After receiving his Ph.D. at DESY (Deutsches Elektronen-Synchrotron) in Hamburg 1993, he worked as a Post-doc at the University of Texas in Austin (HERA-B Experiment). In 1996, he joined the Max-Planck-Institut für Plasmaphysik in Garching, where he was appointed as head of the Energy and System Studies Division in 1999. Today, he is a Full Professor in renewable and sustainable energy systems at the Technical University Munich (TUM), Germany. His research focuses on energy and systems analysis, focusing on urban energy systems, the integration of renewable energy into the power grid, innovative nuclear systems (including fusion), and the methods and fundamentals of energy models.

2. The Power System of Singapore

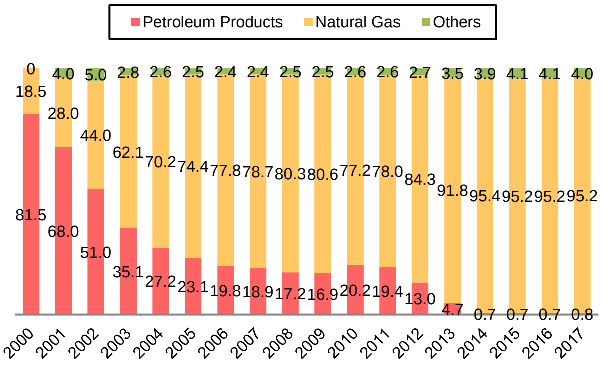


Figure 1. Development of Singapore's power generation mix (all figures in percent).

During the past two decades, Singapore's power generation mix underwent a major shift from oil to natural gas. This was mainly due to the increasing oil price, higher efficiency and lower emissions of natural gas power plants. In the year 2000, the share of oil in the power generation mix was 81.5 %. By today, it has decreased to 0.8 %, whereas the share of natural gas increased from 18.5 % to 95.2 %. The rest comes from coal, waste incineration and biomass. Fig. 1 shows the development of the power generation mix from 2000 to now as published in EMA's yearly "Singapore Energy Statistics".[4]

In 2015, the grid emission factor was 431 g CO_2eq/kWh. In 2016, the installed capacity was 13.4 GW, whereas the peak load was just 6.9 GW. The amount of total electricity generated in 2016 was approx. 50 TWh.

2.1. Potential for renewable energy sources in Singapore

Due to its small land area, the potential for alternative emission-free forms of energy is rather low. Energy from PV may be the only feasible source. In 2014, the Solar Energy Research Institute of Singapore (SERIS) published a solar photovoltaic roadmap for Singapore[10] which claimed that in the best case, by 2050, up to 10 GW of PV could be installed. This includes technological progress which means that in 2050, the efficiency of solar cells will be considerably higher than today. PV panels could be installed on rooftops, facades, artificial floating islands etc. These installations could cover 30 % of Singapore's yearly electricity demand if the demand does not significantly increase by 2050. An alternative could be to import electricity from other ASEAN[1] countries. We performed various studies which show that interconnecting countries in ASEAN could lead to cost and emission reduction in the region.[29,30] As long as the generation potential in Singapore is high enough such that temporary disconnection from the ASEAN grid does not lead to blackouts in Singapore, this option could be considered in the future.

2.2. Modeling of Singapore's power system

Some standard models exist to model power systems, such as the TIMES model generator.[31] Initially, we used TIMES, to set up several scenarios to investigate the development of the electricity demand and supply including photovoltaic power and electrification of transport.[32,33]

In order to analyze the impact of EVs on the power system in more detail, another model was set up in 2012 based on the URBS model.[34] Our model has been continuously extended since then and updated with the current generation system of Singapore. A purely linear version is available as open source software package. In the model, overall costs C are defined as the sum of investment costs C_{inv}, fix costs C_{fix}, fuel costs C_{fuel}, variable costs C_{var} and start-up costs $C_{startup}$ which are calculated from input data:

$$C = C_{inv} + C_{fix} + C_{fuel} + C_{var} + C_{startup} \qquad (1)$$

In the optimization, total costs are minimized. The user can set up the generation system with generation capacities, efficiencies, and maximum and minimum power output. Generation from intermittent renewable sources and demand are modeled as time series. Our version of the model is a mixed-integer linear model for more accurate modeling of start-up costs. Similar to the demand time series, electricity demand of EVs is integrated by using mobility models which output the aggregated demand of all vehicles in form of time series. The model has been used intensively for private EVs. After finishing our research on energy and charging demand for electric taxis and public buses, in the near future, we will perform similar analyses for these types of vehicles as we did for private EVs.

3. Electrification of Singapore's Road Transportation System

3.1. The current transportation system

In order to avoid traffic congestion, the use of private passenger cars is discouraged in Singapore, while the public transport network is constantly being extended and improved. Today, five MRT (mass rapid transport) train lines are in operation. One new line is currently being under construction and two more are under planning. By 2030, the length of the MRT network will be about 360 km, i.e., twice as high as in 2013. Within the Bus Service Enhancement Program (BSEP) that was launched in 2013, the number of public buses has been increased by 1000 by 2017 compared to 2012 numbers. The number of bus services has been increased by 80.[35] With high taxes being imposed on private cars and drivers having to get a Certificate of Entitlement (COE) before being allowed to drive their car on Singapore's roads, the number of private passenger cars is not expected to increase a lot during the next years. Only a limited

[1] Association of Southeast Asian Nations (an organization comprising ten countries in Southeast Asia)

number of certificates is issued every year in a bidding system. In fact, the number of private passenger cars decreased by approximately 3000 from 2013 to 2014. In 2014, about 537 000 (55 %) of Singapore's vehicles were private passenger cars. The number of buses and taxis was 17 500 and 28 700 respectively.

3.2. Electrification of different vehicle types

The charging requirements for different vehicle types depend heavily on their driving profile and mileage. In Singapore, private cars have an average yearly mileage of 17 500 km[2] which corresponds to an average daily mileage of 48 km. Assuming an average speed of 30 km/h to 40 km/h, private cars are parking for more than 22 hours a day. Hence, fast charging may hardly ever be necessary for private EVs, but in contrast, they offer flexible energy demand. The charging energy for EVs can be distributed in an intelligent way over the day such that on the one hand despite their high number, their impact on the power system can be kept low, and they can even offer ancillary services and help integrating high shares of fluctuating renewables (see Section 4).
Buses and taxis however, may require fast charging and consequently offer less room for flexible scheduling. In the following subsections, we will present the methodology and results of our research on the impact of electrification of private passenger cars, taxis and buses on the power system.
This paper considers only unidirectional power flow from the grid into the vehicle. Although some literature considers vehicle-to-grid (V2G) as a viable and even profitable way for EVs to receive incentives[36-39], concerns like battery degradation due to excessive cycling, high battery replacement costs and range anxiety may discourage private drivers to participate in V2G programs. Participation in V2G programs requires vehicles to stay available even after the charging operation has been completed. Viewing that the goal of public EV operators is to provide a reliable and cost-effective service, increase in charging infrastructure cost and vehicle underutilization are viewed as the main reasons preventing participation of public EVs in V2G programs.

3.2.1. Private passenger cars

In Singapore, private passenger cars mainly park in car parks. Hence, these are the only location for charging stations we consider. In the long run, car parks offer the development of an affordable charging infrastructure as installations can be shared by many car owners. In order to determine the spatiotemporal charging demand, a mobility model was developed first. For charging, it is important to know where and when cars are being parked in car parks such that they are available for charging. The initial model was designed in 2012 and had been improved and extended in the following years. It is based on Singapore's official HITS (household income and travel survey) data and publicly available occupancy data of different car parks in Singapore. All this information has been incorporated into an agent-based simulation model which reflects the parking and driving behavior of people in Singapore. The final model was published in 2015.[40] It requires the number of electric cars and days to simulate as input, and the temporal resolution of the simulation. A state machine is used to generate trips. The probabilities of each transition from one state to others are based on the aforementioned data. The model includes different types of passenger cars with different power demand and battery capacities. The battery capacities in the model range from 13 kWh to 55 kWh with an average of 24 kWh. For each trip, the energy demand is calculated. During parking, the cars are available for charging.
An extended version of the power plant model introduced in Section 2.2 with mixed-integer variables was used for this analysis. In this model, all cars are aggregated. This yields the available energy the cars can be charged with in each time step of the optimization of the power plant operation. How much energy to charge during each parking period, is up to the car owners. Based on this information, different charging strategies, i.e., how to distribute the charging energy over each parking period, can be analyzed. The following four charging strategies were considered in this analysis:

- Dumb: Whenever a car is plugged in, it is being charged with the maximum available power.
- Mean: The required charging energy is distributed evenly over the parking period.
- Smart: The car is charged such that it is cost-optimal from power system perspective.
- Smart plus: This is the same strategy as smart with consideration of regulation and reserve.

Various scenarios with up to 600 000 electric passenger cars were analyzed. Table 1 shows the relative increase of overall costs, CO_2 emissions and power plant start-ups for dumb and smart charging and 200 000 and 600 000 EVs. The number of start-ups decreased for all cases except for 600 000 EVs and dumb charging.

Table 1. Increase of overall cost, CO_2 emissions and number of power plant start-ups in percent for different numbers of EVs and different charging strategies.

Increase [%]	Number of EVs (charging strategy)			
	200 000 (dumb)	200 000 (smart)	600 000 (dumb)	600 000 (smart)
Overall cost	2.0	1.8	6.0	5.2
CO_2 emissions	2.0	1.7	5.8	5.0
Number of start-ups	–1.0	–3.0	5.0	–3.0

The load curve for 600 000 electric cars on a weekday in 2012 is shown in Fig. 2. The gray curve shows the load without EVs. The other curves show the load including EVs for the first three different charging strategies. For smart charging, a high portion of the additional demand is shifted to the night time and the load curve becomes almost flat during the day. For dumb charging, the peak load increases by 300 MW, for mean charging by 330 MW, and for smart charging it increases by less than 200 MW. On other days, increases of up to 400 MW have been observed for dumb and mean charging.

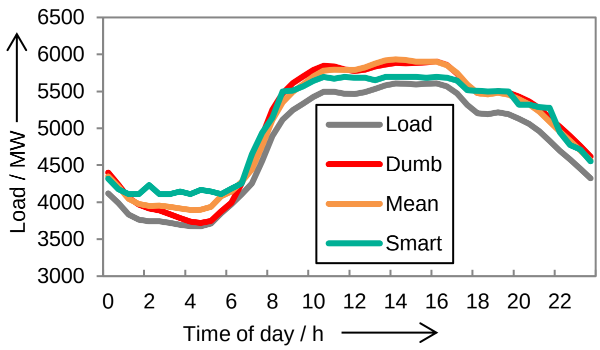


Figure 2. Load curve over one day without EVs (gray) and for different charging strategies.

Generally, increasing the peak load should be avoided and, as can be seen in Fig. 2, smart charging also leads to higher ramps in the morning and evening, which puts additional strain on the power plants. In a later study, we incorporated these factors and included the integration of photovoltaics (see Section 4.2).
In addition to the temporal distribution of the charging demand, we looked at the spatial distribution of the charging energy based on the mobility model. Fig. 3 shows the spatial distribution of the charging energy for 500 000 private EVs on a weekday. The maximum occurs in the east of Singapore where many car owners live. As information on Singapore's distribution grid is unavailable, the impact on it could not be quantified. But the information where most charging demand can be expected can act as a guideline for the power grid operator.

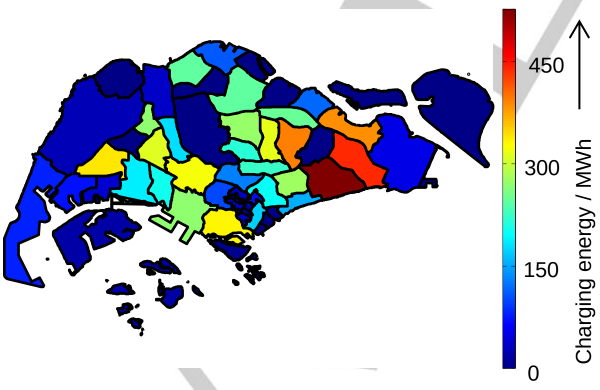


Figure 3. Spatial distribution of the overall charging demand for 500 000 electric passenger cars on a weekday.

3.2.2. Taxis

Taxis are an important mode of transport in Singapore since private cars are expensive and due to governmental restrictions, their number is limited. Switching to electric taxis offers more comfort for drivers and customers and reduces emissions. Even though taxis in Singapore represent only 3 % of the vehicle population, they account for 15 % of the mileage of all vehicles. Many taxis drive in two shifts and reach mileages of up to 750 km per day according to our analysis. In contrast to private cars, electric taxis therefore require larger batteries and fast charging. Hence, an optimal charging infrastructure for electric taxis is harder to design.
The aim of this study was to develop and implement an algorithm which optimized the placement of charging station with respect to the number and vehicle types of electric taxis. Based on the optimization results, recommendations regarding the development of a charging infrastructure and the operation of an electric taxi fleet were derived.
This project was done in collaboration with SMRT Taxis, a Singaporean taxi company, and consisted of three main parts. The first part was to get a deep understanding of today's taxi operation. Therefore, GPS loggers were installed in 50 taxis. The loggers tracked the taxis' position every second over a period of six months. Furthermore, another data set containing the status and position of 3000 taxis over a period of one month was analyzed. These data sets consist of more than 340 million data points in total. In order to increase the efficiency of extracting statistics from the data sets, SQL databases were developed. The second part of this project was to develop an agent-based simulation model in order to simulate the driving patterns of conventional as well as electric taxis. The statistics derived from the data sets served as background of the simulation model. The simulation model is capable to calculate the taxis' mileage and revenues with respect to the number and type of electric taxis, the number and placement of charging stations, and the charging power. The final step was to develop an optimization model which maximized the economic benefit of electric taxis and the charging infrastructure by finding the ideal number, locations, and charging power of charging stations.
The optimization model uses the results of the simulation model. The agent-based driving profile simulation model is built on a supply-based approach. That means that the model uses the recorded driving profiles of conventional taxis as input and reproduces them unless the agents need to recharge the battery. The infrastructure optimization is formulated as a multiple server allocation problem[41] and decides how many charging stations shall be placed at each candidate charging location in order to minimize the taxis' detour and waiting time costs as well as the charging infrastructure costs. The problem is formulated as a mixed-integer linear program which minimizes detour and charging infrastructure costs. Waiting times are considered by a linear constraint which requires a sufficient number of charging stations to ensure zero waiting time.
We analyzed the spatiotemporal charging load of 2949 EVA taxis with a charging power of 160 kW with respect to time and region where charging events occurred.

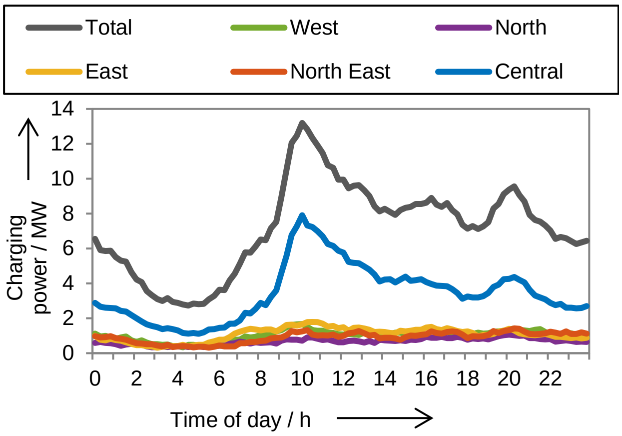


Figure 4. Load curve of 2949 EVA taxis over one day for different regions of Singapore and the total load (gray).

Figure 5. Selected regions of Singapore.

The load curve is shown in Fig. 4. The selected regions are depicted in Fig. 5. The results show that the simulated total charging load ranged from 2.7 MW at 4:45 a.m. to 13.1 MW at 10:30 a.m. The main reason for the peak at 10:30 a.m. is that many taxi drivers are having a break at that time. A similar pattern occurred after the evening peak hour at 8:30 p.m., when the charging load reached another peak of 9.6 MW. The number of vehicles considered in this analysis is about 200 times lower than the number of passenger cars, but the load is just about 25 times lower. Hence, charging of electric taxis has a much higher impact on the power system per vehicle than that of private EVs.
The disaggregation of the charging load into regions shows that by far the highest charging load throughout the day occurred in the central region which also includes the Central Business District (CBD). This is plausible as the spatial density of taxis is the highest in this region. The highest load with 7.9 MW appeared at 10:30 a.m., which contributed to 60 % of the total load. Interestingly, the evening peak at 8:30 p.m. is much smoother and contributed to only 45 % of the total load. In the morning, many customers take a taxi to go from an outer region to the central region which results in a disproportionally high density of taxis in that region after the morning peak hours. In contrast, in the evening many customers go back to the outer regions, which lowers the taxi density in the central region and therewith the charging demand at that time. The optimization yielded that in total, 278 charging stations in 62 locations would be necessary in this scenario using the EVA taxi.
The implemented charging behavior model which is designed to recharge as much energy as possible during breaks had a big impact on the simulated load curves. More intelligent strategies which take the temporal and spatial utilization of charging station into account could cause significantly different load curves.
These strategies could be favorable from the drivers' as well as a charging infrastructure provider's point of view. Drivers could adjust their charging pattern in order to minimize waiting times, which would result in a smoother load curve with lower peaks. In this case, a smaller number of charging stations would be required to keep waiting times at an acceptable level.

3.2.3. Public buses

Similar to taxis, public buses have a high daily mileage. Their curb weight ranges from 10 to 20 metric tons. Including the high demand for air conditioning, their demand per kilometer is considerably higher than that of private cars and taxis. In Singapore, commuters require a card to enter buses or the MRT system. When entering a bus or MRT station platform, they have to tap in with the card. Upon leaving, they have to tap out. The fare is calculated from the distance and means of transport. All tap-in and tap-out events are centrally registered. This generates a large set of data, called CEPAS (Contactless e-Purse Application) data set. The LTA provided us with a set of anonymized CEPAS data for three months of the year 2013. For our research, the trips of each individual bus including driving and dwelling time and the number of passengers in high spatiotemporal resolution were important. In a preprocessing step, the CEPAS data had been aggregated at the level of each individual bus stop-to-bus stop journey. This means that instead of one record per tap-in or tap-out event, the derived data set contains one record per bus stop for each individual bus, with the sum of boarding and alighting passengers at that stop. The arrival and departure times at each bus stop as well as the dwelling time had been derived based on the time between the first and last tap-in and / or tap-out at each stop. This intermediate data set contained 1.2 million records per day. With this data set, we were able to perform a countrywide analysis of the bus energy demand in Singapore in a hypothetical scenario where all buses were electrically powered. In the following, we will present the methodology used to estimate this energy demand and its results. A key parameter for the estimation of the energy consumption of vehicles is the driving profile. For private cars, we could refer to a standard driving cycle. For taxis, we had GPS data in high temporal resolution which enabled us to derive a very accurate model. For buses, however, the available data set didn't contain data about the driving profile of the buses. The only available data to estimate the driving behavior were the arrival and departure times at each stop as well as the distance driven between each stop. In order to derive the energy consumption for buses, we designed a simplified longitudinal dynamics model which was parametrized with the available data in the data set.

In this simplified model, the speed profile of buses consists of a constant acceleration phase (a_+), a constant coasting speed phase (v_1) and a constant deceleration phase (a_-). Between two stops, a bus may go through these phases more than once (e.g., in order to stop at traffic lights). The energy demand is then calculated by adding the energy consumption of each phase.
The energy model for EVs is based on a longitudinal dynamics model which consists of four force components:

$$F_{total}(t) = F_{air}(t) + F_{roll}(t) + F_{climb}(t) + F_{inertia}(t) \quad (2)$$

$F_{air}(t)$ is the aerodynamic force, $F_{roll}(t)$ is the rolling resistance force, $F_{climb}(t)$ is the climbing resistance and $F_{inertia}(t)$ is the inertia force of all components in the drive train. A constant slope based on the elevation difference between each stops is used to calculate $F_{climb}(t)$. The energy consumption was originally given in integral form based on speed and acceleration profiles over time. In order to obtain terms for the energy consumption which don't rely on recorded time profiles but on the available bus stop-to-bus stop information (distance and average speed), the general energy consumption formula was integrated analytically, taking into account assumptions made for each phase (constant acceleration and deceleration / constant speed phase). The resulting formulas only depend on the distance between the stops, the nominal acceleration and deceleration rates and the nominal coasting speed. The distance between the stops came directly from the bus data set. The acceleration and deceleration rates were chosen as constant parameters and the coasting speed was either set as a parameter or estimated based on the departure and arrival time and distance between stops. The equations for determining the energy demand for acceleration, constant speed and deceleration phase are given as follows:

$$E_{a(t)=a_+} = \frac{1}{\eta} \cdot d_0 \left(Mgf + Mg \sin\alpha + M'a_+ + \frac{\rho C_d A}{2} \cdot a_+ d_0 \right) \quad (3)$$

$$E_{a(t)=0} = \frac{1}{\eta} \cdot d_1 \left(Mgf + Mg \sin\alpha + \frac{\rho C_d A}{2} \cdot v_1^2 \right) \quad (4)$$

$$E_{a(t)=a_-} = r_{reg}\eta \cdot d_2 \left(Mgf + Mg \sin\alpha + M'a_- - \frac{\rho C_d A}{2} \cdot a_- d_2 \right) \quad (5)$$

In equations (3) – (5), $d_{0,1,2}$ represent the distance during acceleration, driving at constant speed and deceleration; v_1 is the constant speed during the coasting phase. The other parameters are defined as follows: M is the vehicle mass, f is the rolling resistance, α is the slope angle, M' is the inertial mass, a_+ and a_- are acceleration and deceleration, ρ is the density of air at 25°C, C_d is the air resistance coefficient, A is the cross section area, η is the overall efficiency of motor, inverter and gear box, r_{reg} is the regeneration factor that considers energy gain while braking, and g is the gravitational constant. We also added the energy demand for air conditioning and other electric devices in the bus. This energy model outputs one energy consumption record for each bus stop-to-bus stop trip in the CEPAS data set which yields the energy needed by each bus for each trip between two stops. Since we kept the original level of detail of the CEPAS data, we obtained a highly detailed spatiotemporal estimation of the energy demand for electric buses in Singapore.
The particularity of our energy demand model is its usability on large scale data sets where detailed velocity profiles are not available. To the best of our knowledge, this is the first time the energy requirements for electric public buses for the entire bus network of a megacity of the scale of Singapore are determined.
The results are based on our first analysis of the data for four days of operation in August 2013. The key takeaways from the analysis are as follows. Single decker buses amount to 66 % of the total distance driven, followed by double decker buses with a share of 24 % and articulated buses which account for 10 % of the total mileage. The average distance of a terminal-to-terminal journey for buses is around 20 km. In total, 90 % of the terminal-to-terminal journeys are shorter than 32 km. About 40 % of the buses drive more than 200 km per day. From (3) – (5), the average specific energy demand has been estimated at 1.5 kWh/km, 1.6 kWh/km and 1.9 kWh/km for single decker, double decker and articulated buses respectively.

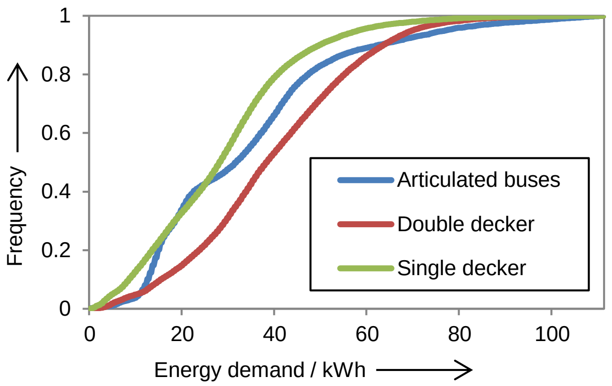


Figure 6. Cumulative distribution of the total energy demand for a terminal-to-terminal journey by bus type.

The average total daily energy demand of all buses in this data set amounts to 1.3 GWh of which 794 MWh (61 %) apply to single decker, 376 MWh (29 %) to double decker and 130 MWh (10 %) to articulated buses. The distribution of the energy demand (Fig. 6) shows that 90 % of the individual terminal-to-terminal bus journeys require less than 50 kWh for single decker and less than 62 kWh for double decker and articulated buses. The distribution of the total energy demand per bus indicates that 88 % of single decker, 69 % of double decker and 63 % of articulated buses require less than 400 kWh for a day of operation. With 300 kWh usable battery capacity, 50 % of single decker, 40 % of double decker and 38 % of articulated buses can cover their daily mileage without recharging during operation.

The regional distribution of the energy demand of electric public buses in Singapore is shown in Fig. 7. The highest demand is located where the density of bus stops and the number of bus lines are highest, which is particularly the case in the planning areas of Orchard, Rochor, Singapore River and Museum. Outside of the central region, we recognize a higher energy demand in the locations of major bus interchanges, for example in Woodlands, Hougang, Clementi and Jurong West.

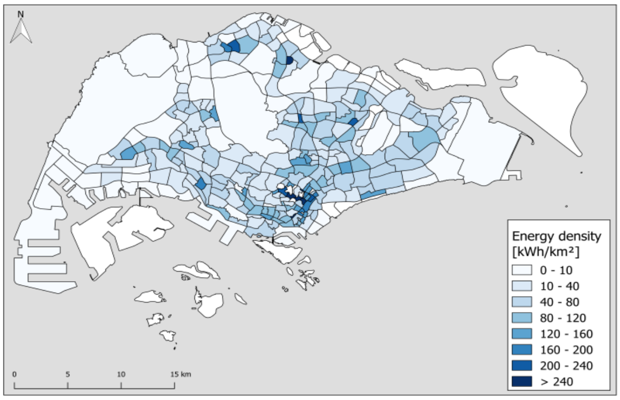


Figure 7. Map of the regional distribution of the energy demand of electric buses.

Fig. 8 shows the load curve of the entire electric public bus fleet for one day of operation. Note the two peaks corresponding to the passenger demand peak hours in the morning at around 8:00 a.m. and in the evening from 4:30 p.m. to 7:00 p.m. of 95 MW and 85 MW respectively. In between, the energy demand reaches a plateau between 60 MW and 65 MW. At the beginning and the end of the daily operation, the load curve is very steep as most services start and end simultaneously. Note that this is the temporal distribution of the energy demand, i.e., while driving, not the charging demand. In order to successfully integrate electric buses at larger scales, our future research will aim at determining an optimal charging infrastructure and schedule considering operational requirements of the bus network and the impact of fast charging on the grid.

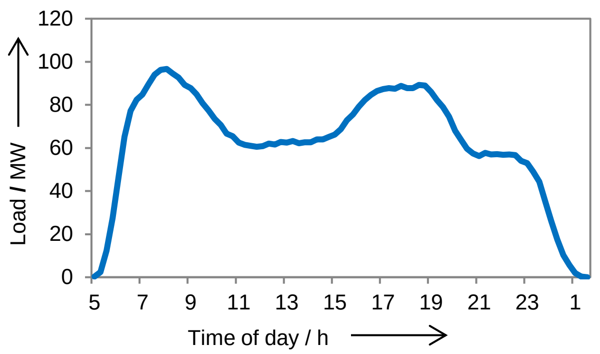


Figure 8. Load curve of a fleet of fully electric public buses on a weekday.

4. Interaction of Electric Vehicles with the Grid

4.1. Ancillary service provision

Advances in battery technology allow for faster charging rates without excessive degradation, but one of the main challenges for transport electrification arises from the relatively longer time required to extend the driving range in comparison to internal combustion vehicles. Although electromobility results in an increase of the overall energy demand, long parking times observed in private vehicles can be used to schedule the charging operation on the one hand to lower the impact on the grid as shown in Section 3.2.1, and on the other hand to provide ancillary services to the power system. If the uncertainty related to the arrival time, parking duration and required range to complete the next trips can be quantified, car park operators could obtain monetary incentives by providing this flexibility in demand response markets.

Liberalization of electricity markets provides opportunities for electric loads to bid their capacities in the energy and ancillary market, thus, allowing load aggregators to obtain revenue by either direct participation in the demand response program or by bidding their capacities as interruptible loads. In a previous study, we considered aggregation of EVs by an independent car park aggregator.[42] This aggregator coordinates the charging status of all vehicles within the carpark and schedules the charging operations by direct control. The aggregator submits reserve bids by providing curtailment of flexible loads during contingencies. Results of this study show that the total system cost could be reduced when compared to the case when only the costs for energy procurement are considered.

In Singapore, the demand response market started operating in late 2016. The program enables contestable consumers to obtain incentives for reduction in the electricity demand when prices are high or when system reliability is compromised. However, the revenue cannot be calculated beforehand and is only settled after the load is curtailed. Any curtailment during market periods with high prices would benefit the load aggregator, provided that the charging operation can be rescheduled to a future market period with lower price.

Battery degradation could become one of the main concerns to prevent EV drivers to participate in demand response programs. Fig. 9 shows experimental results obtained from tests of Lithium-ion rechargeable cells. The decrease in the energy content of the cells based on different combination of initial and final state of charge (SoC) was derived. Later, the batteries were cycled at different C-rates but between a fixed initial and final state of charge. This was used to obtain the aging factor for the batteries.[43] High C-rates could result in additional degradation during market periods with low energy prices or periods with high incentives for provision of ancillary services. We proposed a battery degradation index to compensate drivers for the increased battery aging resulting from the increase in the C-rate resulting from participation as flexible loads.[43] A 50 % reduction in battery aging was achieved without any increase in total system cost. A correct estimate of both energy and reserve prices are essential for maximizing the revenue obtained for participation in ancillary markets. A robust formulation to protect aggregators from imperfect information on prices was presented.[43] Results show that a 4 % reduction in the energy procurement cost can be achieved when aggregators show a risk-averse attitude by expecting higher energy prices. On the other hand, expecting lower incentives for provision of ancillary services result in less flexible loads scheduled, especially when battery aging is considered.

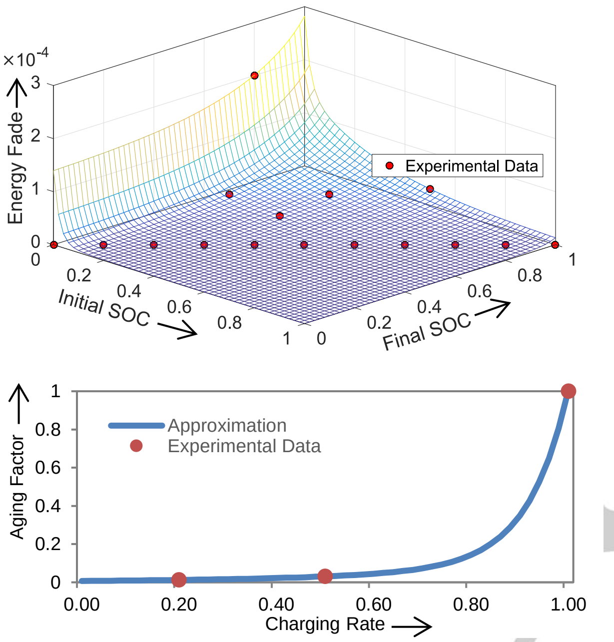


Figure 9. Battery aging parameters: energy fade (top), aging factor (bottom).

Provision of ancillary services by electromobility could benefit both aggregators and drivers. Ancillary services are usually more expensive during the day. New business opportunities are created for load aggregators at commercial or industrial locations that could provide an alternative to residential charging due to the lower system costs. Drivers could not only benefit from lower charging rates but also from the higher number of charging locations.

4.2. Balancing fluctuations of photovoltaic power

Being located close to the equator, solar irradiation in Singapore is high throughout the year. However, due to local weather conditions (rapid changes in cloud cover and other phenomena), high fluctuations occur; particularly from November to February. Consequently, a high share of PV can lead to high fluctuations in electricity supply which pose a high strain on conventional power plants, especially if all available PV power must be integrated. Gas power plants are flexible. However, fluctuations within minutes lead to high ramps or temporary shut-downs of individual power plants, which causes higher cost of operation.[44] Even without fluctuations the morning ramp-up of PV generation and the evening ramp-down cause additional ramps and shut-downs and start-ups of conventional power plants.[45,46] A solution could be energy storage, which however may lead to higher cost of operation.[47] On the other hand, flexible loads such as EVs could offer a solution which even leads to a reduction of cost of operation.

In this study[48], we focused on private electric passenger cars again. We used the same model as in Section 3.2.1 with a few modifications such as the incorporation of ramping costs and we allowed solely the power system operator decide when to charge the cars as long as their state of charge was above 60 % at the end of each parking period, which allowed for high flexibility during the optimization. The aggregated minimum and maximum charging energy of EVs, as well as data on solar irradiance in Singapore in each time step were input as time series. We set the length of the time steps to 15 minutes. Ramping costs C_{ramp} for each power plant in each time step of the simulation were defined as follows:

$$C_{ramp} = R_{lo} c_{r,lo} + R_{hi}(c_{r,hi} - c_{r,lo}) \qquad (6)$$

In (6), R_{lo} and R_{high} are the absolute difference in power output between two adjacent time steps, where R_{lo} applies to the portion of the difference that is less or equal half the maximum technically possible change in power of the power plant, and R_{high} applies to the higher portion. This way, high ramps can be penalized to a higher extent, which is because higher ramps cause higher strain on power plants.[44] Accordingly, different specific ramping cost per megawatt $c_{r,lo}$ and $c_{r,hi}$ are used. C_{ramp} was added to the objective function of the optimization (Eq. (1)). We set up various scenarios varying the installed PV power from 0 to 7.5 GW and the number of electric passenger cars from 0 to 500 000. The optimization used the flexible demand by EVs to balance short-term fluctuations, which lead to smoother operation of the gas power plants with fewer start-ups.

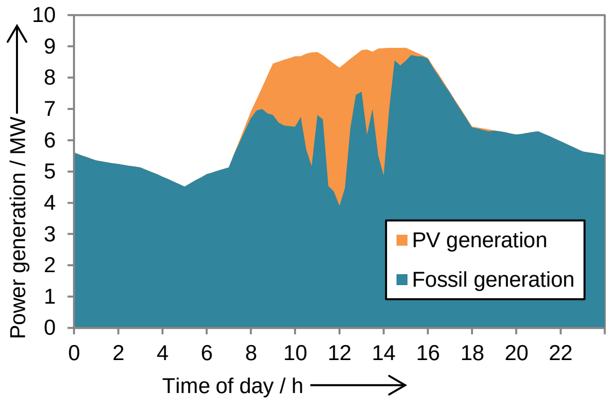


Figure 10. Fossil and PV generation on a day with high fluctuation of PV power output and no EVs.

Figs. 10 and 11 show the generation curve of an extreme day in February in a future scenario in 2050 with a peak demand of approx. 9 GW and 5 GW of PV installed. The solar irradiance and consequently the power generation from PV fluctuated heavily, which generated high ramps in fossil generation and forced temporary shut-downs of fossil power plants during the day. Fig. 10 shows the case when no EVs were included.

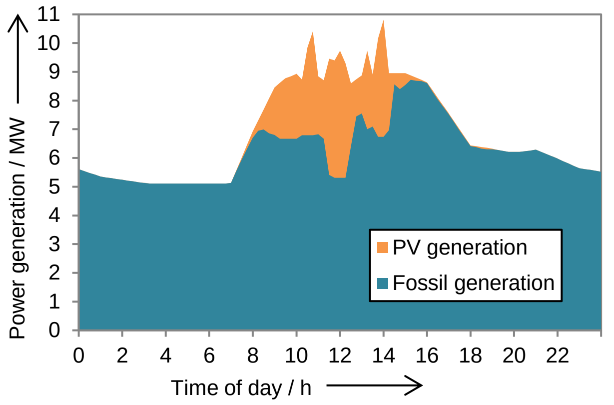


Figure 11. Fossil and PV generation on a day with high fluctuation of PV power output and 500 000 EVs.

In the case of Fig. 11, 500 000 private EVs were included. Most of the additional demand caused by the EVs was distributed during the peak hours in order to smooth the supply curve of the fossil power plants. The rest was used to fill the demand gap between 3 a.m. and 7 a.m. Mainly due to lower fuel costs, specific operating costs decreased with a higher share of PV, compensating increased costs for additional start-ups and ramping. Results also show that EVs can lead to increased specific operating costs when no PV or only 1 GW of PV was installed. With 500 000 electric cars, specific operating costs decreased also for low values of installed PV as the demand could be held rather constant during the night, which reduced ramping and start-up costs. Table 2 shows the specific operating costs for various values of installed PV and numbers of EVs.

Table 2. Operating for costs for different amounts of installed PV and different number of electric passenger cars.

Installed PV [GW]	Operating costs [USD/MWh] for different numbers of EVs		
	0	100 000	300 000
0	62.50	62.70	62.53
1	61.66	61.57	61.71
3	60.32	60.24	60.13

5. Emission Reduction Potential

In this section, we present the results of a study on the emission reduction potential of electromobility in Singapore with today's power generation mix.[49] Aside from greenhouse gases, we considered various pollutants. First, we selected a model to determine vehicle exhaust emissions, then we collected data on today's vehicle fleet of Singapore including emission classes and mileage, obtained information on grid emission factors, and finally compared today's vehicle emissions to additional power plant emissions caused by the electricity demand of EVs.
For our analysis, we chose the model COPERT 4[50] as all required input data were available and we considered country-wide emissions only. Moreover, COPERT 4 uses the Euro emission standard which is used in Singapore. Detailed data on the vehicle population of Singapore including average mileage, vehicle subsector and technology are available. All vehicle categories are subdivided by their fuel type. Motorcycles and cars are further divided by cc rating while the bus population is separated by passenger capacity. Goods and other vehicles are partitioned by type of body and maximum laden weight. The age distribution is given for cars, buses, goods and other vehicles, and motorcycles with the total amount per year or in percent. All data is taken from LTA's annual vehicle statistics.[51] For average mileage and speed of taxis and buses, we used our own data.
Specific emissions from power generation are hardly available. The Energy Market Authority of Singapore regularly publishes values for the greenhouse gases CO_2 and CH_4.[4] Information on polluting emissions of Singapore's power plants is not available. The GREET model however, provides averaged emission factors for pollutants grouped by the source of primary energy and was initially developed to analyze the fuel production in the USA.[52] Since the values used in GREET are specific for the USA, they can only be used as a guideline for emission factors of other countries. We therefore considered the GREET values as the best case and considered a worst case where emissions are assumed to be 50 % higher than in the GREET model.
Considering charging losses, the final electricity demand from the grid results in 18.5 kWh/100 km for electric passenger cars.[53] For bigger passenger cars, other sources suggest values up to 27 kWh/100 km.[54] We therefore chose an average demand of 20 kWh/100 km for the simulation. Due to their larger weight, light duty vehicles have a higher demand which we set to 30 kWh/100km based on existing models. For motor cycles, we chose an average of 8 kWh/100 km accordingly. Due to their much higher weight, battery electric buses require significantly more energy than passenger cars. We used the values derived from calculations in Section 3.2.3.

Table 3. Transport emission reduction potential of EVs for the best and worst case.

Compound	Emission reduction potential (best case)	Emission reduction potential (worst case)
CO_2eq	75 %	62 %
CO	95 %	65%
NO_x	90 %	10%
VOC	90 %	55%

Table 3 shows the exhaust emission reduction potential for CO_2 and various pollutants in the transportation sector. For all compounds, the emission reduction potential is high – even with today's power generation mix. For NO_x, the deviation between best and worst case is highest, which is because NO_x emissions of gas power plants increase in part load operation. Gas power plants in Singapore should operate at a minimum load of 55 %.[55,56] This underlines the need for proper integration of electromobility into the power system.

6. Discussion and Conclusion

In this review, we presented a summary of the research at TUMCREATE in the field of electrification of road transport and its integration into the power system. We showed the prospective additional power and energy demand of electric passenger cars, taxis and public buses. The installed capacity in Singapore is currently high enough to cover the additional demand. However, charging of EVs can on the one hand increase the peak load and put more strain on power plant operation by causing additional ramps and shut-downs and start-ups. Intelligent charging strategies can lower the impact of electromobility on the power system and the grid. Our results also show that EVs could even help integrate solar PV into Singapore's power system. Singapore intends to install solar PV, but has so far been reluctant to install higher shares. As we showed, EVs and act as providers of energy storage that can react quickly to changes in power supply and demand. Electromobility also has a high potential for ancillary service provision and new business models. As Singapore's power generation mix is already rather clean, switching to electromobility will not just reduce local emissions of pollutants, heat and noise, but also country-wide emissions including greenhouse gas emissions. By installing both PV and electromobility, emissions could even be further reduced without increasing operating costs of the power system. Singapore is ready for electromobility and it is currently increasing the number of EVs within the EV test-bed 2 and another electric bus trial to start in 2018. At the same time, more and more test-beds for autonomous vehicles are being set up in Singapore. Driverless vehicles with an optimal driving cycle are more efficient than people-driven vehicles. Moreover, autonomous vehicles that are able to share charging stations by swapping places in a car park or vehicle depot whenever it makes sense, can reduce the number of charging stations and costs as well. Hence, autonomous and electric mobility could benefit from each other.

In future research, we will analyze intelligent charging strategies for electric taxis and public buses. We will also look into further services such as frequency response from EVs, and on the impact of electromobility on distribution level.

Acknowledgements

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) program. We would like to express our gratitude to SMRT Taxis for providing us with detailed GPS and booking data of their taxi fleet. We would also like to thank LTA for giving us detailed CEPAS data over a period of three months, and the Solar Research Institute of Singapore for providing us with data on solar irradiance in Singapore.

Keywords: electric vehicles • electromobility • power system • optimization • smart grid

[1] Department of Statistics Singapore, *Singapore Statistics, Latest Data*, **2016**, http://www.singstat.gov.sg/statistics/latest-data, accessed 7 August 2017.
[2] Land Transport Authority, *Statistics in Brief*, **2015**, https://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/StatisticsinBrief2015FINAL.pdf, accessed 7 August 2017.
[3] Land Transport Authority, *Land Transport Master Plan*, **2013**, https://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/ReportNewsletter/LTMP2013Report.pdf, accessed 7 August 2017.
[4] Energy Market Authority, *Singapore Energy Statistics*, **2017**, https://www.ema.gov.sg/Singapore_Energy_Statistics.aspx, accessed 8 August 2017.
[5] National Climate Change Secretariat, *Singapore's Emissions Profile*, **2016**, https://www.nccs.gov.sg/climate-change-and-singapore/national-circumstances/singapores-emissions-profile, accessed 8 August 2017.
[6] International Energy Agency, *Global EV Outlook 2017*, **2017**.
[7] International Energy Agency, *Global EV Outlook: Understanding the Electric Vehicle Landscape to 2020*, **2013**.
[8] Land Transport Authority, *Key findings from EV Phase 1 Test-bed*, **2014**, https://www.lta.gov.sg/data/apps/news/press/2014/20141208_EVPh2-TestBed.pdf, accessed 10 August 2017.
[9] Land Transport Authority, Economic Development Board, *Joint News Release on EV Phase 2 – Share an Electric Car*, **2014**, https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=b1f98bcd-e4fc-4902-9f9d-08bc2309c3df, accessed 10 August 2017.
[10] J. Luther, T. Reindl, *Solar Photovoltaic (PV) Roadmap for Singapore (A Summary)*, **2013**, accessed 9 August 2017.
[11] "Study on the optimization of charge-discharge cycle of electric vehicle batteries in the context of Singapore": G. B. Shrestha, B. C. Chew in *Australasian Universities Power Engineering Conf*erence (Perth), **2007**.
[12] N. Nezamoddini, Y. Wang, *Risk management and participation planning of electric vehicles in smart grids for demand response, Energy*, **2016**, 116, 836–850.
[13] S. Aghajani, M. Kalantar, *A cooperative game theoretic analysis of electric vehicles parking lot in smart grid, Energy*, **2017**, 137, 129–139.
[14] K. Knezović, M. Marinelli, A. Zecchino, P. Bach Andersen, C.Traeholt, *Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration, Energy*, **2017**, 134, 458–468.
[15] O. Rahbari, M. Vafaeipour, N. Omar, M. A. Rosen, O. Hegazy, J.-M. Timmermans, S. Heibati, P. Van Den Bossche, *An optimal versatile control approach for plug-in electric vehicles to integrate renewable energy sources and smart grids, Energy*, **2017**, 134, 1053–1067.
[16] S. Micari, A. Polimeni, G. Napoli, L. Andaloro, V. Antonucci, *Electric vehicle charging infrastructure planning in a road network, Renewable and Sustainable Energy Reviews*, **2016**, 80. 98–108.

[17] A. Awasthi, K. Venkitusamy, S. Padmanaban, R. Selvamuthukumaran, F. Blaabjerg, A. K. Singh, *Optimal planning of electric vehicle charging station at the distribution system using hybrid optimization algorithm, Energy*, **2017**, 133, 70–78.

[18] Y. Xiang, J. Liu, R. Li, F Li, C. Gu, S. Tang, *Economic planning of electric vehicle charging stations considering traffic constraints and load profile templates, Appl. Energy*, **2016**, 178, 647–659.

[19] "Spatially differentiated energy and environment comparison of diesel and electric buses": D. Honnery, R. Napper, I. Fridman, P. Moriarty in *38th Australasian Transport Research Forum* (Melbourne), **2016**, 1–14 .

[20] Z. Gao, Z. Lin, T. LaClair, C. Liu, J.-M. Li, A. K. Birky, J. Ward, *Battery capacity and recharging needs for electric buses in city transit service, Energy*, **2017**, 122, 588–600.

[21] "Study on power and energy demand for sizing the energy storage systems for electrified local public transport buses": P. Sinhuber, W. Rohlfs, D. U. Sauer in *IEEE Vehicle Power and Propulsion Conference* (Montreal), **2012**, 315–320.

[22] M. Rogge, S. Wollny, D. Sauer, *Fast Charging Battery Buses for the Electrification of Urban Public Transport – A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements, Energies*, **2015**, 8, 4587–4606.

[23] B.-R. Ke, C.-Y. Chung, Y.-C. Chen, *Minimizing the costs of constructing an all plug-in electric bus transportation system: A case study in Penghu, Appl. Energy*, **2016**, 177, 649–660.

[24] "Commercial operation of ultra low floor electric bus for Seoul city route": U.-D. Choi, H.-K. Jeong, S.-K. Jeong in *Vehicle Power and Propulsion Conference* (Seoul), **2012**, 1128–1133.

[25] "E-bus for Akita Prefecture, Japan": H. Utsumi, K. Saito, A. Saito, K. Tanaka, H. Ohmoto in *World Electric Vehicle Symposium and Exhibition* (Barcelona, Spain), **2013**, 1–4.

[26] "Electric city bus and infrastructure demonstration environment in Espoo, Finland": J. Laurikko, M. Pihlatie, N.-O. Nylund, T. Halmeaho, S. Kukkonen, A. Lehtinen, V. Karvonen, R. Mäkinen, S. Ahtiainen in *International Electric Vehicle Symposium and Exhibition* (Goyang, South Korea), **2015**, 1–11.

[27] B. Zhou Y. Wu, B. Zhou, R. Wang, W. Kea, S. Zhang, J. Hao, *Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions, Energy*, **2016**, 96,603–613.

[28] Union Internationale des Transports Publics, *ZeEUS eBus Report*, **2016**.

[29] "Cost Optimal Options for the Future Power Supply of Indonesia, Malaysia and Singapore": J. Stich, M. Mannhart, T. Zipperle, T. Massier, M. Huber in *Proceedings of the 33rd International Energy Workshop* (Beijing), **2014**, 1 – 11.

[30] "Enhancing the Integration of Renewables by Trans-Border Electricity Trade in ASEAN": J. Stich, T. Massier in *IEEE PES Asia-Pacific Power and Energy Engineering Conference (Brisbane)*, **2015**.

[31] IEA-ETSAP, *TIMES Model Generator*, http://iea-etsap.org/index.php/etsap-tools/model-generators/times, accessed 8 August 2017.

[32] M. Wagner, T. Hamacher, *Impacts of Photovoltaics and Electromobility on the Singaporean Energy Sector*, *Energy Procedia*, **2012**, 25, 126–134.

[33] M. Wagner, K. Schönsteiner, T. Hamacher, *Model-based Analysis of Singapore's Energy System*, *Progress in Sustainable Energy Technologies: Generating Renewable Energy*, **2014**, 1, 625–637.

[34] Chair of Renewable and Sustainable and Energy Systems, Technical University of Munich, *URBS – A Linear Optimisation Model for Distributed Energy Systems*, **2017**, https://github.com/tum-ens/urbs, http://urbs.readthedocs.io/en/latest/, accessed 10 April 2017.

[35] Ministry of Transport, *Bus Service Enhancement Programme*. http://www.publictransport.sg/content/publictransport/en/homepage/bus-service-enhancement-programme-bsep.html, accessed 8 August 2017.

[36] E. Sortomme, M. A. El-Sharkawi, *Optimal scheduling of vehicle-to-grid energy and ancillary services, IEEE Trans. on Smart Grid*, **2012**, 3, 351–359.

[37] S. B. Peterson, J. Whitacre, J. Apt, *The economics of using plug-in hybrid electric vehicle battery packs for grid storage, Journal of. Power Sources,* **2010**, 195, 2377–2384.

[38] S. B. Peterson, J. Apt, J. F. Whitacre, *Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization, Journal of Power Sources*, **2010**, 195, 2385–2392.

[39] D. Pelzer, D. Ciechanowicz, H. Aydt, A. Knoll, *A price-responsive dispatching strategy for Vehicle-to-Grid: An economic evaluation applied to the case of Singapore, Journal of Power Sources*, **2014**, 256, 345–353.

[40] "Mobility Model for the Estimation of the Spatiotemporal Energy Demand of Battery Electric Vehicles in Singapore": A. E. Trippe, P. Lopez Hidalgo, M. Lienkamp, T. Hamacher in *IEEE 18th International Conference on Intelligent Transportation Systems* (Las Palmas, Spain), **2015**, 578–583.

[41] O. Berman, Z. Drezner, *The multiple server location problem, Journal of the Operational Research Society*, **2007**, 58, 91–99.

[42] "Charging of electric vehicles and demand response management in a Singaporean car park": D. F. Recalde Melo, H.B Gooi, T. Massier in *49th International Universities Power Engineering Conference (Cluj, Romania)*, **2014**.

[43] D. F. Recalde Melo, A. Trippe, H. B. Gooi, T. Massier, *Robust Electric Vehicle Aggregation for Ancillary Service Provision Considering Battery Aging, IEEE Trans. on Smart Grid*, **2016**, 99, 1–11.

[44] S. Wogrin, D. Galbally, A. Ramos, *CCGT unit commitment model with first principle formulation of cycling costs due to fatigue damage, Energy,* **2016**, 113, 227–247.

[45] "Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart": P. Denholm, M. O'Connell, G. Brinkman, J. Jorgenson, *National Renewable Energy Laboratory*, **2015**.

[46] K. Van Den Bergh, E. Delarue, *Cycling of conventional power plants: Technical limits and actual costs*, *Energy Conversion and Management*, **2015**, 97, 70–77.

[47] T. Zhang, S.-X. Chen, H. B. Gooi, J. Maciejowski, *A hierarchical EMS for aggregated BESSs in energy and performance-based regulation markets, IEEE Trans. on Power Systems*, **2017**, 32, 1751–1760.

[48] "Integration of Renewables in Singapore: Ramp Rate Support Using Electric Vehicles": T. Massier, D. F. Recalde Melo in *7th Innovative Smart Grid Technologies (Auckland)*, **2017**.

[49] M. Storp, *Urban Traffic Pollution Reduction Potential of Electromobility and alternative Fuels in Asian Megacities,* Master Thesis, Technical University of Munich (Munich, Germany) **2015**.

[50] Emisia, Computer Program to calculate Emissions from Road Transport, **2016**, http://emisia.com/products/4, accessed 14 August 2017.

[51] Land Transport Authority, *Annual Vehicle Statistics*, **2016**, https://www.lta.gov.sg/content/ltaweb/en/publications-and-research.html, accessed 14 August 2017.

[52] "Full Fuel Cycle Assessment Well to Tank Energy Inputs, Emissions, and Water Impacts": S. Unnasch, J. Pont, *California Energy Commission*, **2007**.

[53] B. Reuter, K. Schönsteiner, M. Wagner, D. Gleyzes, T. Massier, T. Hamacher, M. Lienkamp, *Life Cycle Greenhouse Gas Analysis for Automotive Applications – A Case Study for Taxis in Singapore*, *Internat. Journal of Smart Grid and Clean Energy, **2014***, 3.2, 127–134.

[54] "Well-to-Wheel Analyses for Energy Consumption and Greenhouse Gas Emissions of Electric Vehicles Using Various Thermal Power Generation Technologies in China": W. Shen, W. Han in *FISITA World Automotive Congress* (Chennai, India) **2013**, 101–115.

[55] KEMA Limited – Energy Market Authority of Singapore, *Review of the LRMC Costs of CCGT Electricity Generation in Singapore to Establish the Technical Parameters for Setting the Vesting Price for the Period 1 January 2009 to 31 December 2010*, **2008**.

[56] Energy Market Authority, *Review of the Vesting Contract Technical Parameters*, **2016**.