Electromobility Potential Index

Evaluating the Potential for Sustainable Success of Electric Vehicles in Megacities

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***Abstract*— Whether or not the introduction of electric vehicles is sustainable in megacities depends on many local conditions such as energy mix, climate and traffic flow. The Electromobility Potential Index (EMPI) is an innovative tool to evaluate each city beforehand. The methodology and structure of this index has an approach that is universally applicable. This work contains the definition of the necessary criteria as well as the evaluation process to analyze the sustainability holistically. A total of 47 worldwide cities, including 21 megacities, are evaluated. The results, which will be presented in this article, give a deep insight of the potential and effects of the introduction of electric vehicles in the cities considered and may help automakers and governments make the right decisions in order to realize sustainable solutions for individual mobility in megacities.**

Keywords— electric vehicles; megacity; sustainability

I. INTRODUCTION

Increasing urbanization coupled with steady economic growth leads to a growing demand for motorized individual transportation [1]. This aggravates the often already problematic environmental impact of CO_2 emissions, fine dust and noise. The introduction of electric vehicles, particularly in megacities, can contribute to the reduction of pollution and thereby increase the quality of life in a city. On the other hand, whether or not electric vehicles could decrease the CO_2 emissions globally as well depends on the respective energy mix of each country. Furthermore, the energy consumption and therefore the range of electric vehicles are highly influenced by the local climate conditions and traffic flow. Last but not least, the economic situation of the city's inhabitants, and subsidies provided by the government will factor into the people's willingness to purchase electric vehicles.

However, whether or not electric vehicles are truly desirable for a specific city depends on a variety of local conditions. A convenient tool to evaluate the potential for sustainable success of electric vehicles in specific cities would therefore be very beneficial to public authorities as well as the automotive industry, but prior to the development of the EMPI, was not readily available.

II. APPROACH

The Electromobility Potential Index (EMPI) shall help decision makers evaluate the potential for a sustainable and successful introduction of battery electric vehicles (BEV) beforehand. The aim was to develop a methodology and structure for the evaluation with a universally applicable approach. In order for the evaluation to be carried out automatically, a software tool was written that accesses existing data, processes them and delivers the outcome of the evaluation. The EMPI analyzes only pure BEV in the form of private passenger cars and so far does not include any form of hybrid electric vehicles or two-wheelers.

III. DEFINITION OF THE EMPI

The EMPI evaluates the potential for the successful introduction of BEV in major cities. Sustainable development, defined in [2] as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", is thus considered as guaranteed, as long as BEV show positive environmental and economic effects on the city and its people. In order to successfully introduce BEV into a city, not only does the population have to accept the new technology, the city itself has to be ready and provide supporting boundary conditions.

Deriving the key topics "sustainability", "user acceptance" and "readiness" from the statements above, we define the following five key performance indicators (KPI) to evaluate the potential for sustainable and successful introduction of BEV in major cities:

The *BEV Consumption* (KPI_W) evaluates the total energy consumption of a BEV under city-specific conditions.

The *Environmental Impact* (KPI_E) analyzes the global balance of CO_2 emissions between the usage of BEV and internal combustion engine vehicles (ICEV) and locally respects any pressure for urgent improvements of the air quality due to pollution. Not considered in this evaluation are environmental impacts due to the production and recycling of the vehicles.

The *BEV Costs* (KPI_C) give an economic forecast for the introduction of BEV in each city by comparing the total cost of ownership (TCO) of a reference BEV and an equivalent ICEV.

The *Infrastructure* indicator (KPI_I) considers the current traffic conditions depending on the efficiency of public transport and road systems and the efforts of a city for building up the necessary charging infrastructure for BEV.

The *Socio-Demographic Conditions* (KPI_S) describe the living conditions of the population and the reliability of the government.

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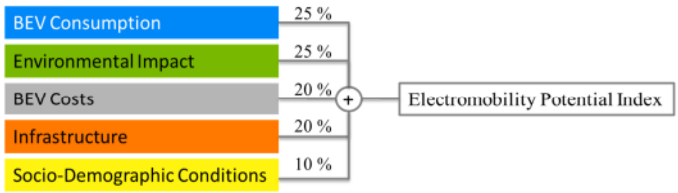

Fig. 1. Key Performance Indicators of the Electromobility Potential Index

The weighting of the five KPI aims to reflect their influences on the above mentioned key topics "sustainability", "readiness" and "user acceptance". KPI_W is considered a major KPI due to its direct influence on the range and costs of the BEV (further described in IV), which are of the highest importance to potential customers according to a worldwide survey presented in [3]. The KPI_E, clearly revealing the effects of BEV on the environment, is seen as another major KPI. Both KPI together are therefore assigned a 50 % contribution to the EMPI, resulting in 25 % each. KPI_C and KPI_I are given 20 % share each, since they are considered to have equal importance, higher than KPI_S with 10 %, since this is mainly seen to be of relevance for early adopters according to [4]. The complete weighting is displayed in Fig.1, thus the EMPI is defined as:

$$EMPI = 0.25(KPI_W + KPI_E) + 0.2(KPI_C + KPI_I) + 0.1KPI_S. \quad (1)$$

The EMPI reveals an overall score between 0 and 100 for each evaluated city, with the critical value defined as 50. Only cities that exceed this value are considered to show acceptable boundary conditions and therefore the potential for a sustainable and successful introduction of BEV. Table I shows the definition of the score board used for the evaluation. All KPI_i and further upcoming performance indicators introduced as PI_i are also defined according to the scoreboard with values between 0 and 100.

TABLE I. SCOREBOARD FOR EMPI AND PERFORMANCE INDICATORS

Indicator value	Indicator ability
100	perfect
90	excellent
80	excellent
70	good
60	good
50	acceptable
40	improvements needed
30	poor
20	poor
10	very poor
0	extremely poor

IV. DEFINITION OF THE KEY PERFORMANCE INDICATORS

A. *BEV Consumption*

The overall energy consumption W_{BEV} is the sum of the consumptions for driving W_{Drive}, heating / air conditioning W_{AC}, and auxiliaries W_{Aux}:

$$W_{BEV} = W_{Drive} + W_{AC} + W_{Aux}. \quad (2)$$

The total consumption is simulated with an electric minivan, which we consider a suitable vehicle type for urban usage, as a reference vehicle under the local conditions of each considered city. The main specifications of the vehicle are shown in Table II. For the calculation of W_{Drive}, an accurate simulation model is available. Whenever possible, measured speed profiles are used as input for the simulation. Otherwise, standard driving cycles, namely Artemis Urban, New European Driving Cycle (NEDC), Federal Test Procedure 72 (FTP-72) and New York City Cycle (NYCC), are taken and, if necessary, slightly modified to suit the local traffic conditions of the respective cities. The necessary load for the heating and/or the air conditioning P_{AC} depends on the temperature, humidity, solar radiation and driving speed. The simulation of the heating load uses data measured from a compact BEV, whereas the air conditioning loads are calculated with a precise computational fluid dynamics simulation. Seasonal changes in climate conditions lead to varying demand for the air conditioning throughout the year. Hence the two months that result in the highest demand for cooling and heating are considered for the simulation of the energy demand for each city. The necessary load for the auxiliaries, P_{Aux}, is assumed to have a constant value of 700 W. For the calculation of the respective energy consumption in kWh/100km, both loads (P_{AC} and P_{Aux}) have to be divided by the average driving speed $v_Ø$ and multiplied with 100 km:

$$W_{BEV} = W_{Drive} + \frac{P_{AC}+P_{Aux}}{v_Ø} \text{ x } 100 \text{ km}. \quad (3)$$

For the determination of KPI_W, two linear functions between three interpolation points are defined: the perfect, acceptable and extremely poor indicator values according to Table I. Having simulated the overall energy consumptions for all cities, the physically lowest possible value of

TABLE II. MAIN SPECIFICATONS OF THE REFERENCE BEV

Description	Constants	Values
Curbweight	m_{curb}	1500 kg
Additional weight (2 passengers)	m_{add}	150 kg
Frontal area	A	2.54 m^2
Drag coefficient	c_d	0.31
Wheel radius	r_w	0.3 m
Tyre roll resistance factor	f_r	0.01
Efficiency DC/DC Converter	η_{DC}	0.94
Efficiency Electric Motor	η_{EMot}	0.94
Efficiency Inverter	η_{Inv}	0.9

$W_{BEV,min}$ = 13 kWh/100km and the highest simulated value of $W_{BEV,max}$ = 33 kWh/100km are assigned to the indicator values 100 and 0, respectively. We consider a consumption of $W_{BEV,50}$ = 23 kWh/100k, which was nearly the average of all simulated values, as acceptable and hence assign it the indicator value of 50. The definitions made above can be described mathematically as follows:

$$KPI_W(W_{BEV}) = 50\times\begin{cases}1+\frac{W_{BEV,50} - W_{BEV}}{W_{BEV,50} - W_{BEV,min}} & \text{if } W_{BEV} \leq W_{BEV,50}\\ 1 - \frac{W_{BEV,50} - W_{BEV}}{W_{BEV,50} - W_{BEV,max}} & \text{if } W_{BEV} > W_{BEV,50}.\end{cases} \quad (4)$$

B. Environmental Impact

The emission balance Em_{bal} compares the well-to-wheel (WtW) CO_2 emissions between BEV and ICEV:

$$Em_{bal} = \frac{Em_{BEV}}{Em_{ICEV}}, \quad (5)$$

where Em_{BeV} is the emissions per distance for the reference BEV and Em_{ICEV} the emissions per distance for a reference ICEV. The reference ICEV is the same as the BEV with assumed 300 kg less weight. BEV are locally free of CO_2 emissions, which is why the global balance Em_{BEV} is the product of the well-to-tank (WtT) emissions $Em_{WtT,BEV}$, resulting from the electricity generation and supply, and the energy consumption of the vehicle W_{BEV}:

$$Em_{BEV} = Em_{WtT,BEV} \times W_{BEV}. \quad (6)$$

The WtW emissions are purely dependent on the individual energy mix and thus the sum of the individual shares of all energy sources α_i multiplied with the respective emission values Em_i as given in Table III. The electrical losses at the charging stations are taken into consideration by applying the factor F_{Charge} of 1.1 so that the WtW emissions are defined as follows:

$$Em_{WtT,BEV} = F_{Charge}\times\sum(\alpha_i \times Em_i). \quad (7)$$

The CO_2 emissions for conventional vehicles Em_{ICEV} arise during petrol production and the actual driving, resulting in $Em_{WtT,ICEV}$ and $Em_{TtW,ICEV}$. These have to be multiplied with the fuel consumption (W_{Fuel}), which is simulated with the mentioned reference ICEV and the same city-specific driving cycles, and the lower heating value of petrol (LHV_{Petrol}):

TABLE III. CO2 EMISSIONS DEPENDENT ON ENERGY SOURCE [6]

Constants	Values	Constants	Values
Em_{Coal}	968.4 gCO2/kWh	Em_{Hydro}	0 gCO2/kWh
Em_{Oil}	720.0 gCO2/kWh	$Em_{Geothermal}$	0 gCO2/kWh
Em_{Gas}	507.6 gCO2/kWh	$Em_{SolarPV}$	0 gCO2/kWh
$Em_{Biofuels}$	100.4 gCO2/kWh	$Em_{Thermal}$	0 gCO2/kWh
Em_{Waste}	100.4 gCO2/kWh	Em_{Wind}	0 gCO2/kWh
$Em_{Nuclear}$	16.9 gCO2/kWh	Em_{Tide}	0 gCO2/kWh

$$Em_{ICEV} = (Em_{WtT,ICEV} + Em_{TtW,ICEV}) \times W_{Fuel} \times LHV_{Petrol}. \quad (8)$$

Inserting (6) and (8) into (5) results in the definition of the emission balance as:

$$Em_{bal} = \frac{Em_{WtT,BEV}\times W_{BEV}}{(Em_{WtT,ICEV} + Em_{TtW,ICEV})\times(W_{Fuel}\times LHV_{Petrol})}. \quad (9)$$

A new performance indicator $PI_{Em,bal}$ is introduced to evaluate the emission balance. An energy mix using only zero emissions renewable energy would lead to $Em_{bal,min} = 0$ and therefore to an indicator value of 100, whereas $Em_{bal,50} = 1$ is considered acceptable. An extremely poor ratio is considered to be $Em_{bal,max} = 1.5$. Thus $PI_{Em,bal}$ is defined as:

$$PI_{Em,bal}(Em_{bal})=50\times\begin{cases}1+\frac{Em_{bal,50} - Em_{bal}}{Em_{bal,50} - Em_{bal,min}} & \text{if } Em_{bal} > Em_{bal,50}\\ 1-\frac{Em_{bal,50} - Em_{bal}}{Em_{bal,50} - Em_{bal,max}} & \text{if } Em_{bal} \leq Em_{bal,50}.\end{cases} \quad (10)$$

The quotient in (9) reflects the real emission balance. In order to highlight the influence of only the energy mix, a second ratio Em_{set} is defined in (11), which does not consider W_{BEV} as a locally dependent energy consumption. Instead, we set the consumption $W_{BEV,set} = W_{BEV,50} = 23$ kWh/100km, which was earlier defined as acceptable, leading to:

$$Em_{set} = \frac{Em_{WtT,BEV}\times W_{BEV,set}}{(Em_{WtT,ICEV} + Em_{TtW,ICEV})\times(W_{Fuel,set}\times LHV_{Petrol})}. \quad (11)$$

Analogous to (10), the performance indicator $PI_{Em,set}$ is defined as:

$$PI_{Em,set}(Em_{set}) = 50 \times \begin{cases}1 + \frac{Em_{set,50} - Em_{set}}{Em_{set,50} - Em_{set,min}} & \text{if } Em_{set} > Em_{set,50}\\ 1 - \frac{Em_{set,50} - Em_{set}}{Em_{set,50} - Em_{set,max}} & \text{if } Em_{set} \leq Em_{set,50}.\end{cases} \quad (12)$$

We defined the total emission performance indicator PI_{Em} as the average of both emission ratios (10) and (12):

$$PI_{Em} = \frac{1}{2}\times(PI_{Em,bal} + PI_{Em,set}). \quad (13)$$

Whenever PI_{Em} is higher than 50, the introduction of electric vehicles is locally considered as sustainable with regards to CO_2 emissions.

However, a PI_{Em} less than 50 may not necessarily indicate that a city would not benefit from the introduction of BEV. For certain cities, the introduction of an electric vehicle may reduce the air pollution enough that the benefits gained from the improvement in the overall air quality outweigh the drawbacks of the increased CO2 emissions.

To account for this, the performance indicator PI_{PM10} is introduced to quantify the local air quality. By following the guidelines stated in [5], $PM_{10,min} = 20$ µg/m^3 is a perfect benchmark whereas $PM_{10,max} = 120$ µg/m^3 is considered an extremely poor air quality condition:

$$PI_{\mathrm{Pm10}} = 100\times\left(1-\frac{PM_{10}-PM_{10,\min}}{PM_{10,\max}-PM_{10,\min}}\right) \text{ for } PM_{10}=\min\{\mathrm{PM}_{10}, 120\}. \quad (14)$$

The pressure to improve the air quality Pr_{Pm10} is linearly dependent on PI_{Pm10}:

$$Pr_{\mathrm{Pm10}} = 100 - PI_{\mathrm{Pm10}}. \quad (15)$$

It can therefore be seen that cities with high PM10 concentrations have a strong pressure to improve the local air quality. This pressure to improve may be accounted for as $\Delta Pr_{\mathrm{Pm10}}$ in the key performance indicator KPI_{E} for cities with unacceptable PI_{Em} values below 50, as well as values within the transitional range between 50 and 60, and is defined as:

$$\Delta Pr_{\mathrm{Pm10}}(PI_{\mathrm{Em}}) = \begin{cases} 0.1\times Pr_{\mathrm{Pm10}} & PI_{\mathrm{Em}} \leq 45 \\ 0.1\times Pr_{\mathrm{Pm10}}\times\frac{60-\mathrm{PI_{Em}}}{60-45} & PI_{\mathrm{Em}} > 45. \end{cases} \quad (16)$$

From above, it is seen that the $\Delta \mathrm{Pr}_{\mathrm{Pm10}}$ of cities with a PI_{Em} of less than 45 is a maximum of 10 points, while with a PI_{Em} between the values of 45 to 60, the $\Delta Pr_{\mathrm{Pm10}}$ decreases linearly from this maximum value. This is in order to avoid the instance where a city with a low PI_{Em} unfairly overtakes a city with a higher PI_{Em}.

Hence, taking into account the above conditions, the *Environmental Impact*, which evaluates the ecological effect of electric vehicles for each city is given as follows:

$$KPI_{\mathrm{E}}(PI_{\mathrm{Em}}) = \begin{cases} PI_{\mathrm{Em}} & \text{if } PI_{\mathrm{Em}} > 60 \\ PI_{\mathrm{Em}} + \Delta Pr_{\mathrm{Pm10}} & \text{if } PI_{\mathrm{Em}} \leq 60. \end{cases} \quad (17)$$

C. BEV Costs

The TCO performance indicator PI_{TCO} compares the total costs, consisting of acquisition and ownership costs (*CostAcq* and *CostOwn*), between a BEV and an equivalent ICEV:

$$PI_{\mathrm{TCO}} = \frac{TCO_{\mathrm{BEV}}}{TCO_{\mathrm{ICEV}}}\times 100 = \frac{CostAcq_{\mathrm{BEV}} + CostOwn_{\mathrm{BEV}}}{CostAcq_{\mathrm{ICEV}} + CostOwn_{\mathrm{ICEV}}}\times 100. \quad (18)$$

The acquisition cost for electric vehicles $CostAcq_{\mathrm{BEV}}$ is the addition of the costs for the basic vehicle $Cost_{\mathrm{Base}}$, battery $Cost_{\mathrm{Bat}}$, electric motor $Cost_{\mathrm{EMot}}$ and power electronics $Cost_{\mathrm{PowEl}}$:

$$CostAcq_{\mathrm{BEV}} = Cost_{\mathrm{Base}} + Cost_{\mathrm{Bat}} + Cost_{\mathrm{EMot}} + Cost_{\mathrm{PowEl}}. \quad (19)$$

In order to compare the costs more realistically and emphasize the regional differences, the estimation of $Cost_{\mathrm{Bat}}$ does not assume the usage of the same battery in each city. Instead, a fixed range $Range_{\mathrm{set}}$, defined as 150 km, is set for the BEV to achieve. Considering this, $Cost_{\mathrm{Bat}}$ is dependent on the energy consumption of the vehicle W_{BEV} and additional factors for the usable capacity f_{SOC}, ageing effect f_{Ageing} and backup f_{Backup} of the battery and on the estimated costs per kWh $Cost_{\mathrm{Bat,kWh}}$:

$$Cost_{\mathrm{Bat}} = \left(Range_{\mathrm{set}}\times W_{\mathrm{BEV}}\times f_{\mathrm{SOC}}\times f_{\mathrm{Ageing}}\times f_{\mathrm{Backup}}\right)\times Cost_{\mathrm{Bat,kWh}}. \quad (20)$$

The acquisition cost for conventional vehicles $CostAcq_{\mathrm{ICEV}}$ is the sum of the costs for the engine $Cost_{\mathrm{Engine}}$ and gearbox $Cost_{\mathrm{Gearbox}}$, added to $Cost_{\mathrm{Base}}$:

$$CostAcq_{\mathrm{ICEV}} = Cost_{\mathrm{Base}} + Cost_{\mathrm{Engine}} + Cost_{\mathrm{Gearbox}}. \quad (21)$$

The cost of ownership *CostOwn* for the BEV is the energy consumption W_{BEV} multiplied by the local price for electricity $Cost_{\mathrm{Elec}}$, or in the case of the ICEV, the fuel consumption W_{Fuel} multiplied by the local price for fuel $Cost_{\mathrm{Fuel}}$, added to the respective estimated maintenance factors $Cost_{\mathrm{Maint}}$, and finally multiplied by the respective total mileage $Mile_{\mathrm{tot}}$. For reasons of simplification, taxes and insurances are not considered. Thus the costs of ownership are defined as:

$$CostOwn_{\mathrm{BEV}} = \left(W_{\mathrm{BEV}}\times Cost_{\mathrm{Elec}} + Cost_{\mathrm{Maint,BEV}}\right)\times Mile_{\mathrm{tot}}, \quad (22)$$

$$CostOwn_{\mathrm{ICEV}} = \left(W_{\mathrm{Fuel}}\times Cost_{\mathrm{Fuel}} + Cost_{\mathrm{Maint,ICEV}}\right)\times Mile_{\mathrm{tot}}. \quad (23)$$

The performance indicator PI_{GDP} reflects the wealth level of a city and is dependent on the individual gross domestic product *GDP*, we set GDP_{mean} = 25,000 USD per capita as an acceptable value and GDP_{max} = 70,000 USD as ideal, following the actual range of realistic GDP values.

Efforts of the government to encourage BEV are evaluated in the performance indicator PI_{Enc}. The evaluation is done with a matrix taking into account financial subsidies and other incentives and will not further be described in detail here.

The overall key performance indicator KPI_{C} consists of the three defined performance indicators, giving the evaluation of costs the highest share of 50 %. Furthermore, governmental encouragement, with 35 %, is considered as more important than the actual wealth of a city, leading to an overall definition of the key performance indicator as:

$$KPI_{\mathrm{C}} = 0.5PI_{\mathrm{TCO}} + 0.15\, PI_{\mathrm{GDP}} + 0.35PI_{\mathrm{Enc}}. \quad (24)$$

D. Infrastructure

The capability of the road network to deal with the amount of vehicles in a city is evaluated as PI_{Road}, which is dependent on the ratio between the total road length l_{Road} and the total number of vehicles n_{Veh}. According to [7] the ratio shall be kept above 6 meters per car. Since additional vehicles such as two-wheelers or busses occupy the roads as well, a ratio of 5 meters per vehicle is considered acceptable. Thus PI_{Road} is defined as:

$$PI_{\mathrm{Road}} = x\times 10\, m^{-1} \quad \text{with } x = \min\left\{\frac{l_{Road}}{n_{Veh}}; 10\, m^{-1}\right\}. \quad (25)$$

According to [7] a rail network is absolutely necessary for cities with a population density of least 11000/m^2. Therefore the importance of the rail network I_{Rail} is introduced and corresponds to an importance $I_{\mathrm{Rail}} = 1$ for those very dense cities. However, the value then decreases linearly with decreasing population density and can be represented by

$$I_{Rail} = \frac{\mathrm{PopDens}}{11000} \text{ for PopDens} = \min\{\mathrm{PopDens}; 11000\}. \quad (26)$$

The evaluation of the public transport system PI_{PT} relies on the availability of rapid rail transport, and is a function of the evaluated length of the railway available $l_{\mathrm{Rail,eval}}$ and I_{Rail}:

$$PI_{\mathrm{PT}} = 50 + \left(50 \times l_{\mathrm{Rail,\,eval}} \times I_{\mathrm{Rail}}\right). \tag{27}$$

The evaluated length of the railway available $l_{\mathrm{Rail,eval}}$ is defined as:

$$l_{\mathrm{Rail,\,eval}} = \begin{cases} \frac{l_{\mathrm{Rail}} - 50}{50} & \text{if } l_{\mathrm{Rail}} < 50 \\ \frac{l_{\mathrm{Rail}} - 50}{250 - 50} & \text{if } l_{\mathrm{Rail}} \geq 50 \end{cases} \text{for } l_{\mathrm{Rail}} = \min\{l_{\mathrm{Rail}};250\}. \tag{28}$$

As can be seen in the equation above, the ideal l_{Rail} value of 250 km (or more) corresponds to an $l_{\mathrm{Rail,\,eval}} = 1$, while the minimum acceptable length of 50 km corresponds to $l_{\mathrm{Rail,\,eval}} = 0$. Anything less would result in a negative value, thereby decreasing the PI_{PT}.

The next performance indicator is the PI_{Charge}, an indicator of a city's commitment to build up a charging infrastructure for BEV. It is determined with a qualitative evaluation of the current and planned charging infrastructure and includes as well special treatments such as dedicated lanes for BEV.

The overall key performance indicator for *Infrastructure* KPI_I is thus a weighted sum of PI_{Road}, PI_{PT} and PI_{Charge}:

$$KPI_I = 0.3PI_{\mathrm{Road}} + 0.3PI_{\mathrm{PT}} + 0.4PI_{\mathrm{Charge}}. \tag{29}$$

E. Socio-Demographic Conditions

Several studies found that early adopters of electric vehicles are generally well educated and enjoy a high quality of living [3,4]. The Human Development Index (HDI), prepared by the United Nations [8], is a standardized reference value between 0 and 100 that indicates the degree of development and economic impacts on human living conditions of a country. Considered factors for the HDI are: life expectancy, education level, alphabetization and standard of living. Since high living standards are favorable for the successful introduction of BEV, the performance indicator PI_{HDI} defines a value of $HDI = 67$ as acceptable, leading to the linear dependency:

$$PI_{\mathrm{HDI}} = 1.5HDI - 50 \quad \text{for } HDI = \max\{HDI;33\}. \tag{30}$$

The Mercer Quality of Living Index QoL is a city-specific index that includes 10 key categories for quality of living (e.g. socio cultural environment or housing) [9]. PI_{QoL}evaluates this value as previously done in (30):

$$PI_{\mathrm{QoL}} = 1.5QoL - 50 \quad \text{for } QoL = \max\{QoL;33\}. \tag{31}$$

Furthermore, it is assumed that the government plays a key-role for the introduction of electromobility. The corruption index I_{Cor} provided by [10] is hereby a strong factor to forecast the success and failure of major public projects and can be directly taken as the value for the performance indicator PI_{Cor}:

$$PI_{\mathrm{Cor}} = 10I_{\mathrm{Cor}}. \tag{32}$$

The key performance indicator KPI_{S} highlights the variables quantifying the living standard. A stronger weighting is given to PI_{HDI}, because it is considered to be the more holistic and suitable index. Thus the KPI_{S} is defined as follows:

$$KPI_{\mathrm{S}} = 0.5PI_{\mathrm{HDI}} + 0.2PI_{\mathrm{QoL}} + 0.3PI_{\mathrm{Cor}}. \tag{33}$$

V. Database

A new database for the evaluation of electromobility in megacities was developed. Therefore, the largest urban agglomerations ranked by population size in 2010 were chosen. According to the United Nations, the largest city in this ranking is Tokyo with 36.93 million inhabitants, followed by Delhi with 21.94 million, and Mexico City with 20.14 million [11]. For a global distribution, further major cities were selected even if those have less than 10 million inhabitants and thus don't qualify to be called megacities. The scope of this work includes 21 megacities and 26 global cities.

As megacities, especially in developing countries, change and grow very rapidly, there is a need for up-to-date and reliable data of the same base year for a valid comparison between cities. Due to the high availability of data, the year 2008 was chosen as the base year. If, however, only data prior to 2008 is available, this was adjusted with specific growth rates.

VI. Results

The overall EMPI results with the breakdown of each of the key performance indicators discussed earlier in this paper are shown in Fig. 2. There are huge differences between each of the cities with regards to the sustainability for the usage of electric vehicles. In total, 32 out of 47 cities meet or exceed the critical value of $EMPI = 50$. It can be seen that the 15 highest scores are widely distributed between wealthy cities in North America, Europe and Asia, although none of those show perfect or excellent boundary conditions for the introduction of electric vehicles. The best-performing and only cities with an $EMPI > 70$ are Paris, San Francisco and Hong Kong.

The evaluation also reveals that most of the lower performing cities are located in developing Asian countries. The main reasons for the low scores are the poor ratings in the KPI_{W} and the KPI_{I}. Ho Chi Minh City (HCMC), Dhaka, Tehran and Jakarta show exceptionally low results. These cities currently have too many areas where improvements are necessary, before the usage of electric vehicles may be considered as sustainable.

Fig. 3 displays the simulated energy consumptions for air conditioning W_{AC} for selected cities in Asia. Despite very similar tropical climate conditions in most of the analyzed cities and thus similar demand on cooling power P_{AC}, the energy W_{AC} display large differences, revealing the dependency on local traffic conditions. The cities representing high W_{AC} such as HCMC, Dhaka and Jakarta experience severe traffic congestion, bringing the average driving speed $v_{\varnothing}$ down considerably. The energy consumption for the auxiliaries W_{Aux} is also affected by $v_{\varnothing}$ in the same way, it can therefore be deduced that $v_{\varnothing}$ may be a key indicator for the overall EMPI evaluation.

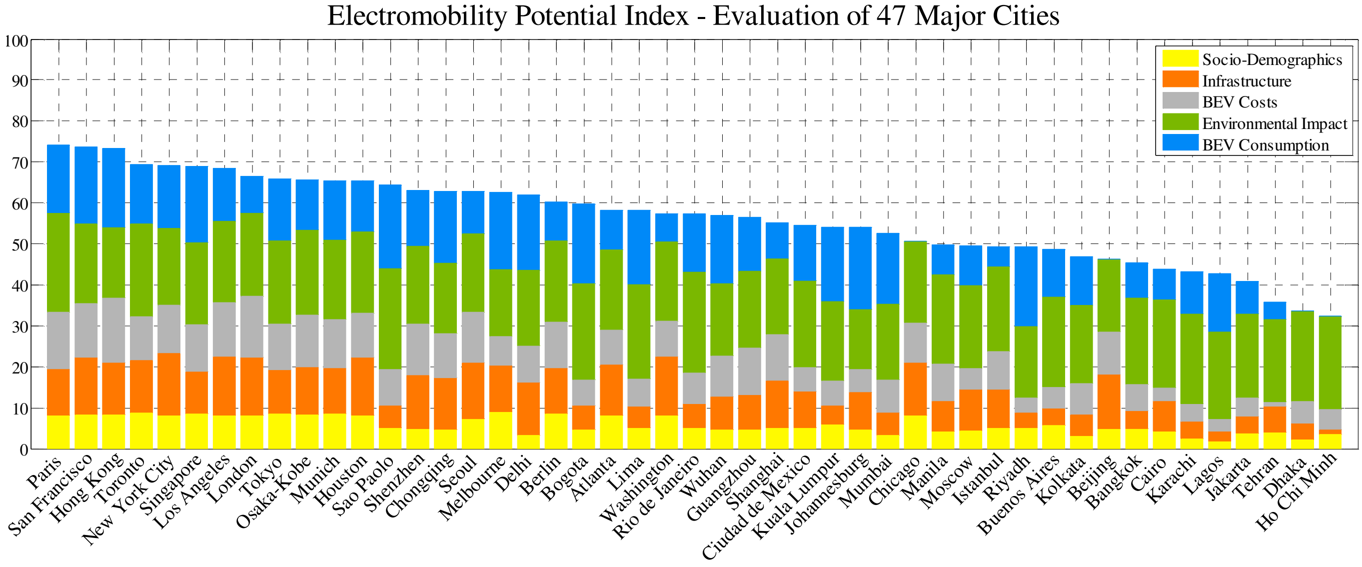

Fig. 2. Electromobility Potential Index for 47 major cities

In order to further verify this, Fig. 4(a) shows the overall EMPI as it relates to the average speed $v_Ø$. From this it can be seen that with $v_Ø \geq 23$ km/h the EMPIs are almost always all acceptable ($EMPI > 50$), and unacceptable with $v_Ø < 17$ km/h where the introduction of BEV is not sustainable. If 17 km/h $\leq v_Ø < 23$ km/h, however, it may be considered a transition zone, as although most of the EMPIs are in the acceptable range, there still exists some values which are below 50.

To gain a better understanding, in Fig. 4(b), a new variable VHDI is introduced – the product of the average speed $v_Ø$, and the *HDI*:

$$VHDI = v_Ø \times HDI. \quad (34)$$

It can be clearly seen from the figure that whenever the VHDI value of a city is greater than 1300, the EMPI is almost always well within the acceptable range. This provides a simple initial indicator to quickly determine whether or not electric vehicles are currently the right choice for a particular city. Further detail and more in-depth insights on the city's suitability may then be obtained with the EMPI.

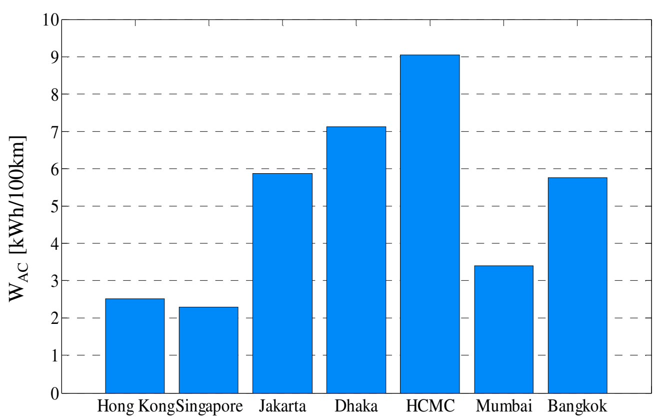

Fig. 3. Energy consumption for air conditioning in selected Asian cities

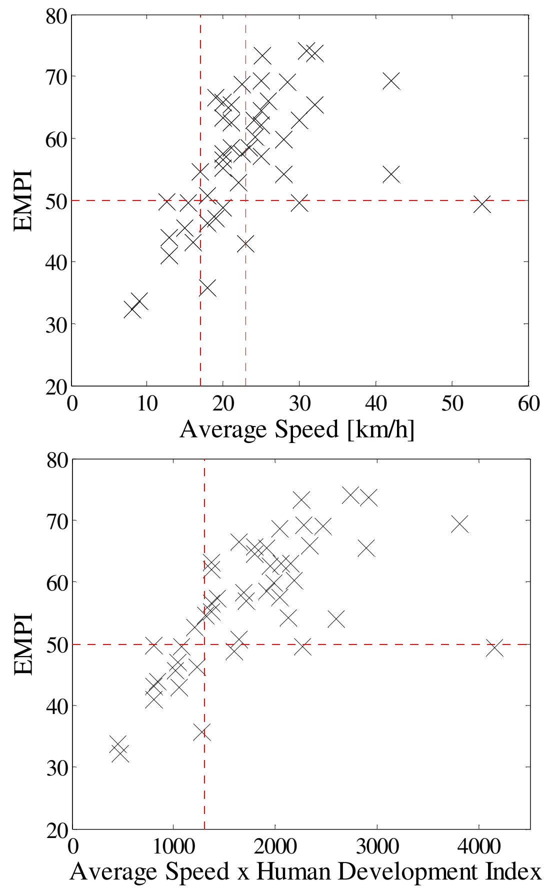

Fig. 4. (a) Correlation between EMPI and Average Speed (*top*) (b) Correlation between EMPI and VHDI (*bottom*)

VII. Conclusion & Outlook

We have developed the EMPI as a unique and powerful tool to quickly evaluate the potential for sustainable success of introducing BEV in any city. The EMPI results depend highly on reliable data and great emphasis was placed on the data collection, which was carried out to the best of our knowledge and abilities. However, as the data were taken from various different sources, it is hard to fully guarantee the trustworthiness and uniformity of the data. Furthermore, the data we have used are from 2008, which for rapidly changing megacities might already be considered outdated. In this case, a dynamic database with up-to-date information on all the cities considered would be ideal.

It was shown that the average speed $v_{\emptyset}$ had a significant effect on the overall EMPI results, but there may be other input data similarly affecting the evaluation. A sensitivity analysis of the input will therefore be carried out in the near future. Identifying which inputs have the greatest impact, would be highly advantageous especially in determining the uncertainty allowed during data collection.

The robustness of the calculation of the EMPI has to be validated by varying the weighting factors of the five KPIs and checking if there are very large variations in the results. Initial validation tests showed the tool to be robust, but more in-depth analysis may still be carried out, for example also with the weighting factors of the PIs making up the KPIs.

This innovative tool, with the evaluation of the EMPI clearly based on the five KPIs and its PIs, has proven its concept with reliable results and offers the possibility to find any critical and improvable values of each city, and could therefore help public authorities concentrate their efforts in improving the relevant factors, consequently encouraging a cleaner form of urban mobility.

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References

[1] Y. Hayashi, K. Doi, M. Yagishita and M. Kuwata, “Urban Transport Sustainability: Asian Trend , Problems and Policy Practices,” European Journal of Transport and Infrastructure Research, vol. 4(No 1), pp. 27–45, 2004.

[2] United Nations, “Report of the World Commission on Environment and Development, Our Common Future,” 1987.

[3] Deloitte, ”Unplugged: Electric vehicle realities versus consumer expectations,”2011.

[4] McKinsey&Company,”Elektromobilität in Megastädten: Schon 2015 Marktanteile von bis zu 16 Prozent,”2010.

[5] WHO, “Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide,” 2005.

[6] J-F. Concawe, “Well-to-wheels Analysis of Future Automotive Fuels and Power trains in the European Context”, European Commission Research Centre, 2011.

[7] Y. Hayashi, “Transport Solutions for Congestion and Climate Change Control in Developing Mega-Cities,“ in LTA Academy JOURNEYS Sharing Urban Transport Solutions, pp. 39–48., November 2010.

[8] United Nations Development Programme, “Human Development Report,” 2011.

[9] Mercer, “Quality of Living Report 2012,” 2012.

[10] International Transparency, “Corruption Perceptions Index 2011,” 2011.

[11] United Nations, “World Urbanization Prospects The 2009 Revision Highlights,” 2010.