Costs and Benefits of Electric Vehicles and District Cooling Systems: A case study in Singapore

Report

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1 Abstract

Urban heat brings negative consequences for communities, their people and their assets. Different strategies and measures could be introduced to reduce urban heat and increase Outdoor Thermal Comfort (OTC). However, these strategies and measures, not only brings with diverse levels of benefits, but also result in differing costs. Typically, a Cost-Benefit Analysis (CBA) is used to assess the cost and benefits of policy interventions. Yet, there are situations in which it is difficult to measure the benefits of a heat reducing measure in monetary terms, making a CBA difficult to implement. In such cases, a Cost-Effectiveness Analysis (CEA) could be applied as an alternative method. In this study, we implement a CEA to assess the effects of two urban heat mitigation strategies related to new technologies: a district cooling system on the one side and the electrification of the vehicle fleet on the other side. We perform our assessment in a study site located in the City Business District (CBD) area in Singapore. We evaluate the costs and the effects of the two technologies applied to the study area. Hereby, the main benefit we are interested in is OTC, but also in final energy consumption and greenhouse gas emissions. In this study, we use the Physiological Equivalent Temperatures (PET) as a proxy measure for OTC (i.e. the lower, the better). We compare different implementation scenarios for both technologies, with different degrees of the technologies' applications (i.e. 33%, 66%, 100%). We also assess the Business-As-Usual (BAU) scenarios, i.e. the scenarios without any additional implementation of the new technologies. Our results suggest that, on the one hand, the implementation of 100% District Cooling Systems presents the highest net-benefits compared with the BAU scenario. In fact, this scenario presents the highest PET improvement (-1.1^{o}C) at rather low costs (- 10.78%) compared to the BAU. Furthermore, this scenario brings the highest additional positive effects on energy consumption and greenhouse gas emissions. On the other hand, a 100% electrification of buses only presents the highest net-benefits as it brings an improvement in PET (-0.71^{o} C) at only a 0.6% increase of the costs compared with BAU. However, the 100% electrification of the vehicle fleet presents the highest PET reduction (i.e. -0.91^{o}C) as well as highest reductions in energy consumption and greenhouse gas emissions across all scenarios, yet at the highest additional costs (i.e. +11.48%) compared with the BAU. In addition to these results, policymakers might consider people's level of acceptance and support for the implementation of specific urban heat mitigation measures. This aspect could be studied by means of Willingness-to-Pay elicitation. Overall, our study gives valuable insights into the costs and benefits of the implementation of new technologies for heat mitigation purposes in Singapore.

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2 Introduction

Hot and humid weather results in a wide range of negative consequences for communities, their people and their assets. Economy, health, well-being, human behaviour, infrastructures and the natural environment are all affected by very high daily temperatures and by humid weather conditions. Urban warming and Urban Heat Island (UHI) tend to yield an exacerbation of these effects. Any degree by which we can lower the temperature comes along with additional costs but also benefits. The higher the net benefits are, the more the liveability and resilience of a country are improved. Different strategies or measures to lower the temperatures imply costs and benefits to countries like Singapore as a whole as well as to different communities and different groups of people within society.

To the best of our knowledge, there is no study estimating and comparing the net-benefits of heat mitigation measures for Singapore. More general studies show that economic losses caused by global climate change could be 2.6 times higher in cities with UHI effects than in other cities (Estrada et al. 2017; Golden 2004). Urban heat may result in GDP losses of up to 10% until 2100 (Estrada et al., 2017). Examples show that the increased use of air-conditioning alone may cost 0.1-0.3% of GDP (Miner et al. 2016). This implies that reducing urban heat and increasing Outdoor Thermal Comfort (OTC) entails a huge potential for net-benefits for the society in terms of health, productivity, cognitive performance and overall well-being.

In this report, we analyse the net-benefits of two different heat mitigation strategies in Singapore, i.e. the electrification of vehicle fleets and district cooling. Comparing the respective estimates for different strategies or measures may enable policymakers to make reasonable and welfare-enhancing decisions for their country.

Cost-Benefit Analysis (CBA) is a core tool used in public policy to evaluate the net-benefits of policy interventions (Quah and Mishan, 2007). To perform a CBA it is necessary that both, costs and benefits can be expressed in monetary terms. However, there are cases in which the benefits of a policy intervention cannot be easily monetarized (see chapter 4.1). In these cases, a Cost-Effectiveness Analysis (CEA) could be applied instead. A CEA helps to identify those intervention(s) that reach a given goal (i.e. reduction of the temperature of 1 degree or the improvement of a heat-mitigation-success indicator) at the lowest possible costs.

In this report, we apply a CEA approach to assess the two above mentioned measures in a specific area of Singapore. To assess the benefits, we focus on the Physiological Equivalent Temperature (PET) index, which captures how changes in the thermal environment affect perceived human outdoor thermal comfort (Chirag and Ramachandraiah, 2010; Heng and Chow, 2019). In addition, we consider secondary benefits, like reductions in final energy consumption and Greenhouse Gas emissions related to the implementation of district cooling systems or electric vehicles.

The cost items differ according to the urban heat mitigation strategy that is under consideration. In any case, costs can be expressed as total Equivalent Annual Costs for each mitigation strategy and scenario considered. Cost items consist of discounted and annualized capital costs as well as of operating costs.

The aim of our assessment of costs and benefits related to urban heat mitigation strategies is to gain insights on the net benefits of specific urban heat mitigation measures in Singapore, i.e. district cooling systems and the electrification of entire vehicle fleets. We implement the assessment in a particular site of Singapore.

3 Study area description, mitigation strategies and scenarios

In this Section, we will describe our site area, the two mitigation measures under evaluation and the scenarios considered for our analysis.

3.1 Study area

In this report, we study the effectiveness of two technologies to mitigate urban heat in a specific site in the Central Business Area (CBD). This area is situated at the south-eastern coastline of the Singapore island.

Our site area is part of a new development within the CBD area and covers 800 x 800 m2 with a mix of some existing building and brownfield (see Figure 1). We chose the site because the fact that it is in development offers a realistic chance to implement new heat mitigating strategies. The Singapore agencies provided us with figures on building types in the site: 60% of the buildings are office buildings, 20% retail buildings, 10% hotels, and 10% residential buildings.

In this study site, we evaluate the costs and the effectiveness of a District Cooling System and of electric vehicles in the area, once the area is fully developed. Furthermore, we consider different implementation scenarios for each of the mitigation measures. The evaluation of these specific mitigation strategies in this particular study site are part of the scope of the Cooling Singapore project.

Figure 1: Study area in the Central Business area (CBD), indicated in the red box.

3.2 Mitigation strategies and scenarios

We analyse three possible scenarios for the implementation of the two mitigation strategies under consideration (see Table 1 for a description of the scenarios). The two strategies are district cooling systems and the electrification of vehicles. These mitigation strategies are related to new technologies and are currently not commonly used in Singapore. Hence, an assessment of the related costs and the effectiveness of the measures is relevant for decision makers. No previous study is available to discuss these aspects for Singapore. Our analysis could help decision and policy makers to decide whether to support or not to support the implementation of district cooling systems or electric vehicles, in the study site and beyond.

For each strategy, we consider three scenarios: the implementation of the strategy at a level of 33% (S1), 66% (S2) or 100% (S3). For the electrification of vehicles, we also evaluate two additional scenarios, in which we consider the electrification of all the buses only (S4) and of all cars only (S5). Costs and effectiveness of all scenarios are assessed in comparison with a BAU scenario (B0), which represents the perpetuation of the current situation without any implementation of urban heat mitigation measures. The BAU scenario is hence our benchmark.

Table 1: Possible scenarios evaluated for the implementation of each mitigation measure.

Mitigation measures	B0 (BAU)	S1	S2	S3	S4	S5
Electric Vehicles	No Electric Vehicles	**33% of the fleet electrified** 66% of the fleet non-electrified	**66% of the fleet electrified** 33% of the fleet non-electrified	**100% of the fleet electrified**	**100% buses Electrified** 100% of cars non-electrified	**100% cars electrified** 100% of buses non-electrified
District Cooling Systems	All cooling is decentralized	**DC satisfies 33% of the cooling demand** 66% of all cooling decentralized	**66% of cooling demand** 33% of all cooling decentralized	**100% of cooling demand**	-	-

4 Methods

4.1 General scope of our analysis

In this Subsection, we present the framework within which we analyse costs and benefits. the effectiveness related to urban heat mitigation strategies. As mentioned in Section 3, we do this analysis in the form of a case study. We assess the replacement of traditional vehicles by electric vehicles and the introduction of a district cooling system in our study area located in the CBD.

In general, urban heat mitigation measures yield specific costs as well as specific benefits. These benefits encompass a large variety of positive effects resulting from reduced urban heat like, for instance, improved health of the population, increased work productivity and hence increased GDP figures, or a reduction in air-conditioning needs and hence a ceteris-paribus reduction in energy demand. In addition, the different heat mitigation measures might result in several positive side effects like a reduction in noise and pollution, once conventional vehicles are replaced by electric vehicles.

In this study, given the time and budget constraints, we were not able to study all these benefits in detail. The scope of potential benefits is far too broad and the analyses of monetarized benefits, which we would need for a CBA, are very complex and not well explored so far. Hence, a comprehensive assessment of benefits under the framework of a CBA would require essentially bigger time budgets to arrive at reliable results. Therefore, instead of analysing monetary benefits from urban heat mitigation strategies in its entirety, we mainly focus on a key intermediary indicator for the multitude of positive effects, i.e. on the PET. The PET is an index widely used as an index for OTC that captures how changes in the thermal environment can affect an individual’s outdoor thermal comfort (Deb and Ramachandraiah, 2010; Heng and Chow, 2019). The lower the PET, the better the OTC.

The scope of our study is hence to estimate PET changes resulting from the implementation of our mitigation strategies in our study site. We will then compare these changes with the monetary costs required to bring the respective PET changes about. However, even though we mainly focus is on OTC improvements, i.e. on PET changes as our main benefit, we also consider secondary benefits derived from the implementation of the strategies. Among these secondary benefits, we focus on a decrease in energy consumption and a decrease in greenhouse gas emissions. These secondary benefits will contribute to a more comprehensive analysis of the effects of urban heat mitigation measures and derived policy recommendations.

Assessing the costs on the one hand and the PET changes on the other hand enables us to calculate the costs needed to achieve a PET reduction of 1 degree Celsius. This calculation refers a specific strategy (district cooling or electric vehicles) as well as a specific implementation scenario (see Table 1) in a specific area in the CBD. Expressing the respective costs per one unit of PET reduction gives us the so-called Cost-Effectiveness Ratio (CER) (Briggs and Gray, 2000; Chau and Burnette, 2000; Briggs and O'Brien, 2001).

CERs can then be compared between the different urban heat mitigation strategies and their respective implementation scenarios. Such a comparison provides decision makers with important insights when being confronted with choices between different urban heat mitigation strategies, given that the financial resources for implementing such strategies are limited.

In the following, we will first show how the CER is calculated (Section 4.2). Furthermore, we will elaborate on principles how to assess costs of district cooling measures and of the electrification of vehicles (Section 4.3). In Section 4.4., we will show the principles for PET measurements and also a metric to estimate the secondary benefits (i.e. a reduction of energy consumption and greenhouse gas emissions). Finally, in Section 4.5., we will show how CER may serve for decisions making.

4.2 The Cost-Effectiveness Ratio CER

As mentioned before, we will assess the CER for two mitigation strategies: a District Cooling System and the electrification of vehicles. We assess annual costs and PET changes. Furthermore, for each mitigation strategy, we consider varying implementation scenarios of the respective measures (see Table 1). In both cases, we look at an implementation of the respective measure at 33%, 66% or 100% of the area. These different coverage percentages characterize our so-called scenarios (S). For our two mitigation strategies, we will compare the cost-effectiveness ratios of every scenario s to the current situation, which we call "scenario B0" or "Business as Usual" (BAU).

As explained above, the benefits B of urban heat mitigation strategies or scenarios will be measured by PET changes. This means that we compare the PET value for a scenario S with the PET value in scenario 0, which gives us $\Delta B_s = (B_s - B_0)$. This difference is also referred to as the mean effectiveness of a scenario (Briggs and O'Brien, 2001). In our analysis ΔB is typically lower than zero if we take PET as indicator of benefits. To facilitate the reading, we make this term positive, by considering the absolute value term $|\Delta B_s|$. The PET value, which we consider in our analysis is specified as the average daily PET calculated between the 7:00am – 10:00am as well as 4:00pm – 7:00pm, when people are on the sidewalks and in the most exposed place in the study site (see Section 4.4.1 and refer to Adelia et al.(2020) for more details).

The costs C of urban heat mitigation strategies or scenarios will be measured by differences in the Equivalent Annual Costs (EAC) (denoted C^{EAC}) between a scenario S on the one side and the BAU scenario on the other side: $\Delta C^{EAC}{}_s = (C_s^{EAC} - C_0^{EAC})$. This difference is referred to as mean costs (Briggs and O'Brien, 2001). The EAC of a scenario is calculated according to the formula:

$$C^{EAC} = \frac{NPV_r^T}{1-(1+r)^{-T}} \quad (1)$$

where NPV = the Net Present Value of the costs

T = number of periods of lifespan of the investment

r = discount rate

As usual, the NPV is defined as follows:

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (2)$$

where C_t are the sum of all CAPEX and OPEX costs in an individual future period t of the heat mitigation project (t = 0,…,T).

To account for the different distribution of costs over time, all costs in all scenarios are discounted and their values in the decision point of time (t=0) are taken into account. This makes the costs of different scenarios comparable, even if the distribution of costs over time is different between the different scenarios.

The Cost-Effectiveness Ratio (CER) of an urban heat mitigating scenario s is then defined as follows:

$$CER_s = \frac{(C_s^{EAC} - C_0^{EAC})}{|B_s - B_0|} = \frac{\Delta C^{EAC}{}_s}{|\Delta B_s|} \quad (3)$$

The CER_s shows the costs, which have to be paid for cooling systems or electric vehicle fleets in order to achieve a 1-degree reduction of PET compared to the BAU scenario. The smaller a CER_s is, the better is the scenario from a cost-effectiveness perspective and hence, having in mind our limitations on the definition of benefits of urban heat mitigation strategies, also from a cost-benefit perspective.

In the following two Sections 4.3 and 4.4, we will now elaborate on principles of assessing the costs of our two sample strategies for urban heat mitigation as well as on principles of PET measurements. Section 4.5. will describe how CER values can serve for decision purposes.

4.3 Estimation of Costs

In the estimation of costs, we differentiate between Capital Expenditures (CAPEX) and Operating Expenditures (OPEX). CAPEX costs consist of the funds needed to purchase major physical infrastructure and goods, which are required for the implementation of a heat mitigation strategy or a measure (Bierman and Smidt, 2012). Such costs essentially occur during the initial year of a measure or project, while there are some smaller investment expenditures in later years, during the lifespan of a project (Bierman and Smidt, 2012). OPEX costs, on the other hand, represent the day-to-day expenses necessary to operate District Cooling Systems or electric vehicles fleets.

In order to take into account that different heat mitigation strategies vary with respect to the distribution of costs over time as well as with respect to the time horizon of specific measures, we focus on the EAC. EAC indicates the cost per year of owning, operating, and maintaining a system over its lifetime (Jones and Smith, 1982; Bierman and Smidt, 2012). The EAC is often used to compare costs of measures with unequal lifespans (Plebankiewicz et al., 2018; Moulton and Mao, 2019). For the two urban heat mitigation strategies we consider, we have a lifespan of 50 years for the District Cooling Systems and of 17 years for the electric vehicles fleet. The timespan of electric vehicles is set to 17 years because LTA vehicle registration expires after 17 years and buses cease operation after the registration expiry (see more details in Section 5.1). For the District Cooling System instead, the lifetime of the entire system is estimated to be 50 years, even though single components might deviate (see more details in Section 5.2). The discount rate used in this study for both measures was 3%.[1]

The CAPEX and OPEX for electric vehicles and for District Cooling Systems were calculated based on the following list of items:

1) *For the Electric Vehicles:*
   a) *CAPEX type costs:*
      i. *Infrastructure costs (i.e. charging stations);*
      ii. *Acquisition costs (cars and buses)*
   b) *OPEX type costs:*
      i. *Maintenance costs*
      ii. *Energy costs*
      iii. *Personnel costs (bus captains and cleaning staff)*
      iv. *Insurance costs*
      v. *Road tax costs*

2) *For District Cooling Systems:*
   a) *CAPEX type costs:*
      i. *Investment costs*
   b) *OPEX type costs:*
      i. *Maintenance costs*
      ii. *Operational costs*

More details on the cost assessment of different heat mitigation measures and scenarios can be found in Section 5.

[1] Singapore's inflation rate averaged 2.51% from 1962 until 2020, while in June 2013 the Monetary Authority of Singapore (MAS) instructed financial institutions to adopt a 3.5% "stress test" interest rate under the Total Debt Servicing Ratio framework. However, the Singapore Government's cost of capital averaged 2.15% from 2020. Therefore, we decided to take 3% discount rate as a mean value between the MAS recommendation and the Singapore's cost of capital.

4.4 Estimation of Benefits

In this sub-section, we define three different metrics to assess benefits related to the introduction of a district cooling system or the electrification of the vehicle fleet in the study site. The three indicators we use are the PET as an indicator for outdoor thermal comfort (OTC), the final energy consumption (FEC) and Greenhouse Gas emissions (GHG) during operation. Given our constraints, CER calculations are only done for benefits in the form of PET reductions. More information about the assumptions and calculations behind the three indicators and their operationalization can be found in the "Mesoscale Assessment of Anthropogenic Heat Mitigation Strategies" Technical Report from the Cooling Singapore project produced by Adelia et al. (2020).

4.4.1 Metric 1: Outdoor Thermal comfort

Outdoor thermal comfort is the key variable we are interested in. The PET index is used as an indicator for OTC perception. Hence, PET is our most important benefit indicator. Typically, PET changes capture how temperature changes affect individual's outdoor thermal comfort (Deb and Ramachandraiah, 2010; Heng and Chow, 2019). Using the PET index as an indicator for OTC perception presents several advantages: 1) PET combines outdoor climatic conditions (wind, T_{mrt}, air temperature and humidity) and thermo-physiological factors (activity of humans and clothing); 2) PET has a thermo-physiological background and so it gives the real effect of the sensation of climate on human beings; 3) PET it is measured in °C and can therefore be easily related to common experience; 4) PET does not rely on subjective measures and; 5) PET is a useful indicator in both, hot and cold climates (Deb and Ramachandraiah, 2010).

Reporting unit: PET on the most exposed area in the study site. This means that our PET results were only estimated for the most vulnerable areas during the hottest periods of the day (see Adelia et al, 2020 for more details of the most exposed area and PET estimations). For Singapore, the goal is that the PET should be low.

4.4.2 Metric 2: Final Electricity Consumption (FEC)

Final energy consumption is the total energy consumed by end-users (see Adelia et al, 2020 for more details of simulation inputs and estimations of the final electricity consumption). We focus on energy use from transport (vehicles) and buildings (including district cooling systems). No energy losses or energy consumption in upstream processes are included. There are three sources of energy relevant to our study: electricity, gasoline and diesel. For fuels, we quantify the energy content via the Lower Heating Value (LHV).

Reporting unit: Final energy (electricity and fuel) consumed per year [GWh/ yr]. The goal is that FEC is low.

4.4.3 Metric 3: Greenhouse gas emissions (during operation) (GHG)

Electricity production and internal combustion engines (ICE) vehicles are major sources of GHG emissions, which contribute to climate change. They also emit CO_2, CH_4, N_2O and fluorinated GHGs. Our study assesses GHG emissions from transport (electricity and motor fuel consumption) and buildings (electricity consumption, including district cooling). For the sake of simplicity, we only count emissions within Singapore and during operating phases (see Adelia et al, 2020 for more details on simulation inputs and estimations of greenhouse emissions).

Reporting unit: Thousand tonnes of equivalent CO2 emissions per year [kT CO_2e/ yr]. The goal is to have low GHG emissions.

4.5 Using CER for decision purposes

Benefits and costs are the two relevant decision parameters in our analysis. In principle, PET values as well as costs of new scenarios can be lower or higher than PET values and costs of the BAU scenario. This is shown in Figure 2 below.

Since we are interested in mitigating urban heat, no measure or scenario that results in a higher PET value than the BAU will be considered as reasonable or eligible. Hence, the NW and SW sectors of the plane in Figure 1 can be excluded. Among those scenarios, which yield a lower PET value than the scenario “0” (sectors NE and SE), the ones with negative CER values (in the SE sector) would be most preferable. They would represent a win-win situation in the sense that a lower PET value can be achieved with lower costs than in the BAU scenario. The choice between different scenarios will have to focus essentially on the SE and also the NE sectors in Figure 2.

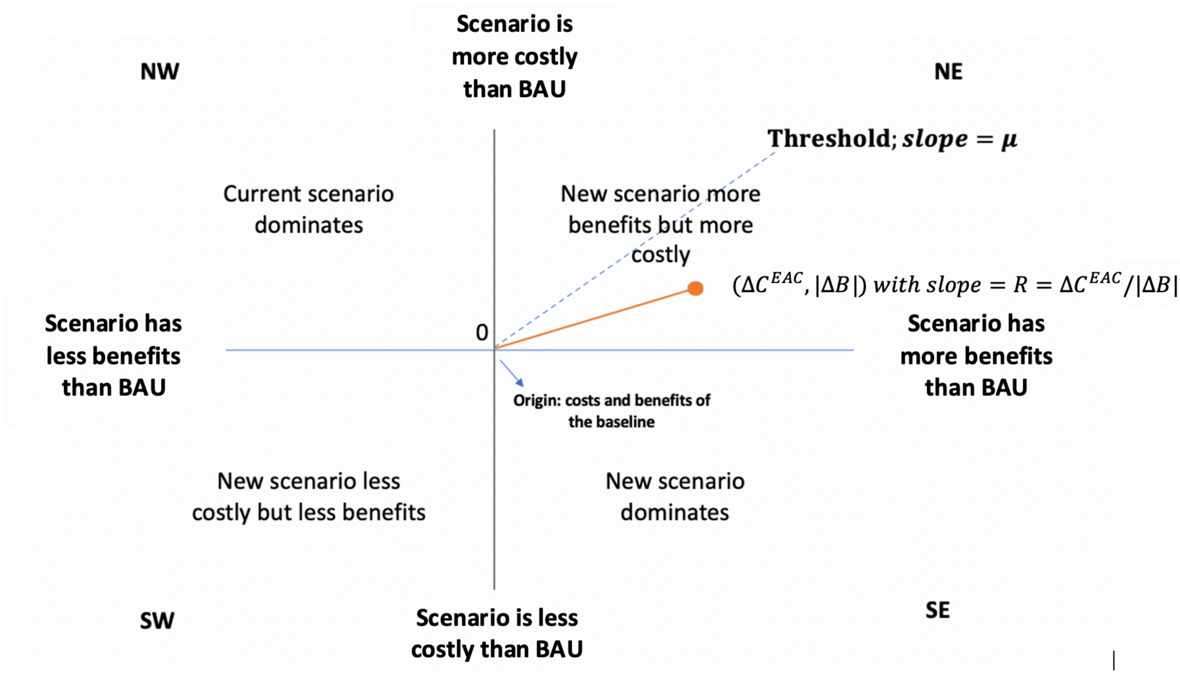


Figure 2: *Cost-Effectiveness plane* diagram (Black, 1990)

Scenarios in the SE sector in Figure 2 are dominating the BAU scenario with respect to benefits and costs. They would hence be preferable for decision makers searching for urban heat mitigation measures.

Within the NE sector, those scenarios that lie on a rather low line (low gradient) are more preferable than others since they guarantee a given benefit at rather low additional costs. Hence, the gradient in the NE sector in Figure 2 would be a criterion for decision makers to look at. They should opt for scenarios that are on the lowest possible gradient line in the NE sector.

For the NE sector, there might be an additional requirement that the CER is below a *threshold line (see line with slope* μ), which would be an externally-set level of the maximum costs that are considered acceptable for achieving a given reduction in PET. Such a threshold could, for instance, be derived from the society's Willingness-To-Pay (WTP) for PET reductions. If such a threshold exists, decision makers would have to make sure that chosen scenarios are below the respective line in the NE sector of Figure 2.

Hence, the following decision rules for decision makers can be set up:

1) Choose dominating scenarios from the SE sector.
2) If there is no dominating scenario and there is a threshold for the CER, choose scenarios for which the respective CER is lower than the threshold μ, i.e., those for which (2) holds:

$$CER_s = \frac{\Delta C^{EAC}}{|\Delta B|} \leq \mu \qquad (4)$$

3) If more than one scenario complies with rule (1) or rule (2), choose the scenario with the lowest CER, i.e., the one that is on the lowest gradient line. If two scenarios are on the same gradient, they are equally good from a CER perspective, although representing different levels of costs and benefits. Here it the depends on the question of how urgent PET value reductions are. The more urgent they seem to be, the more a scenario should be selected that is on the lowest gradient line and rather far to the right. Also benefit metrics 2 and 3 should be considered.

Apart from the decision rules just explained, we recommend that policy makers consider the secondary benefits of a scenario (i.e. energy consumption and greenhouse gas emissions).

As mentioned before, policy makers may consider the population's WTP with respect to the implementation of urban heat mitigation measures (see Borzino et al, 2020 for details).

5 Results

In this sub-section, we present the results in costs, benefits and cost-effectiveness calculation for each the mitigation strategies under evaluation.

5.1 Electric Vehicles

5.1.1 Costs

Assumptions and simulation inputs

The timespan of electric vehicles is assumed to be 17 years because LTA vehicle registrations expire after 17 years and buses cease operation after the registration expiry. As mentioned above, the discount rate chosen in the assessment of costs is 3% (see Subsection 4.3 for details). In the estimation of costs, we consider the costs faced by the government, the costs faced by the private sector and finally the aggregated costs of both sides. We estimate the costs for the BAU and for each of the 5 scenarios described in Section 3.2, Table 1.

Only a small amount of the daily kms run by cars and buses refers to our study area. We only calculated the costs related to this study area. To do so, we first estimated CAPEX and OPEX costs for the buses and cars and for the total amount of kilometres per car and day. Then, we considered only 2.64% of the total costs for buses and 3.18% for cars, as these are the percentage of costs dedicated only to our study area (see Table 3).

Table 3: Simulation inputs for the calculation of costs.

Simulation inputs	Amount	Comment
Buses		
Number of lines	13	
Number of Single-deck buses	178	
Number of Double-deck buses	89	
Number of kilometres/bus/day	324.5	As each bus only transit in the study area 8.57km/day, we consider only the 2.64% of the total costs for the study area
Number of kilometres/bus/day within the study area	8.57	
Infrastructure		
Number of charging stations for buses in the study area	49	
Number of charging stations for cars in the study area	4159	
Cars		
Number of private cars	80200	
Number of kilometres/car/day	47.95	As each car only transit in the study area 8.57km/day, we consider only the 3.18% of the total costs for the study area
Number of kilometres/car/day within the study area	1.52	

Following the simulation inputs from Table 3, we display the number of buses (both internal combustion engines (ICE) and electric vehicles (EV)) and cars (both ICE and EV) as well as the number of charging station for the BAU and each alternative scenario. Table 4 displays the number of cars, buses and charging station considered to estimate the costs and the benefits for each scenario. Once the total costs are estimated, we only count for 2.64% of the total costs for buses and for 3.18% of the total costs for cars given that only these percentages are costs relevant for the study site.

Table 4: Simulation inputs. Number of buses, cars and charging stations for the BAU and each scenario.

	BAU	S1	S2	S3	S4	S5
Number of:	**No Electric Vehicles**	**33% of the fleet electrified** 66% of the fleet non-electrified	**66% of the fleet electrified** 33% of the fleet non-electrified	**100% of the fleet electrified**	**100% buses Electrified** 100% of cars non-electrified	**100% cars electrified** 100% of buses non-electrified
Double-deck bus ICE	89	60	29	-	29	89
Single-deck bus ICE	178	119	59	-	59	178
Double-deck bus EV	-	29	60	89	-	-
Single-deck bus EV	-	59	119	178	-	-
ICE cars	80200	52932	26466	-	80200	-
EV cars	-	26466	52932	80200	-	80200
Charging stations EV buses	-	16	32	49	49	-
Charging stations EV cars	-	1372	2745	4159	-	4159

ICE: internal combustion engine; EV: electric vehicles

Investment and Operational Costs

In the estimation of the costs, we considered CAPEX and OPEX of electric vehicles as described in Section 4.1. The description of each item, the assumptions as well as the sources are reported in Appendix 1. For the electric vehicles (EV), the CAPEX type of costs are the acquisition costs as well as the infrastructure costs. We report the CAPEX costs in Table 5.

We further report the OPEX costs for ICE and EV buses. EVs typically have low maintenance costs (see Appendix 1 for details). Hence, personnel costs (bus captain and cleaning staff) for EVs represent a higher percentage of the total operational costs compared with ICE vehicles. Figure 3 shows the respective shares for buses.

Table 5: Details of CAPEX (acquisition and infrastructure costs) for buses and cars.

Electric vehicles- CAPEX	Internal combustion engines (ICE)	Electric Vehicles (EV)	Comments	Source
Acquisition costs				
12m Double deck	$ 741,000.00	$ 967,000.00		LTA, Tender 2018
12m Single-deck	$ 550,000.00	$ 757,000.00		LTA, Tender 2018
Cars	$ 105,000.00	$ 120,000.00	For ICE cars, it was considered a Toyota Corolla Altis 1.6. For electric cars , it was considered a Nissan Leaf Electric 24kWh.	Market price 2020
Infrastructure costs				
Charging stations		$ 85,000.00	The charging station needs to be replaced every 5 years. In the total costs, it was considered equipment installation and operation costs. We consider also the expected decrease in costs overtime (see Appendix 1 for details)	NCCS and Eri@n, 2017

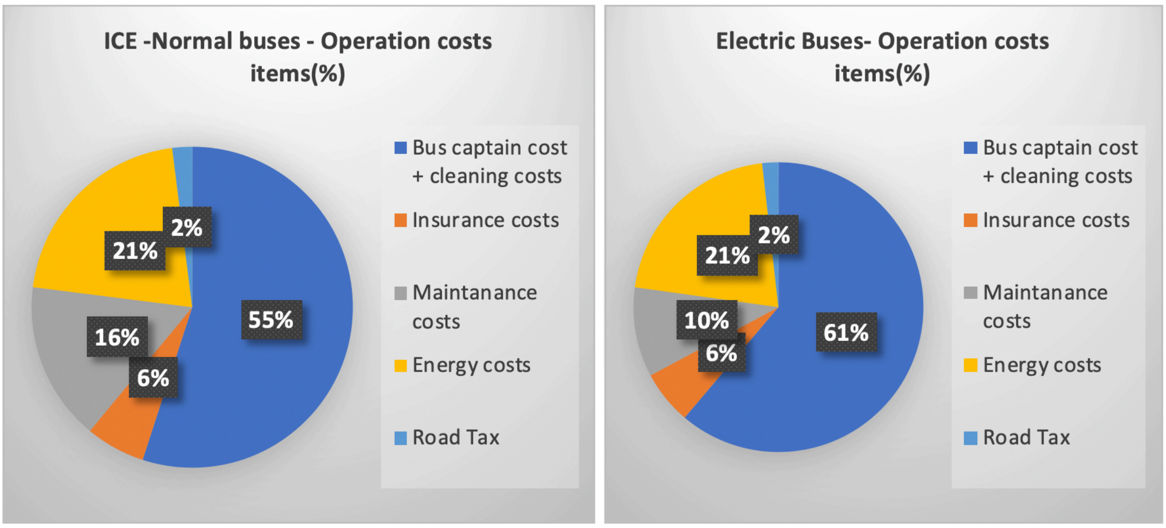


Figure 3: Operational costs comparison between ICE and EV buses.

Equivalent Annual Costs

Table 6 presents the final EAC for the BAU scenario and each of the scenarios for the electric vehicles described in Table 1 and following Section 4.1. The costs presented in Table 6 are only the costs for the study site.

We calculated the aggregated EACs (for the government and for the private sector) as well as the EACs only faced by the government or the private sector. In the government costs, we considered the CAPEX and OPEX from the ICE and EV buses as well as the subsidies for the acquisition of electric cars and the tax rebates following Budget 2020 (Singapore Ministry of Finance, Singapore Budget, 2020). Following the Singapore Budget 2020, we assumed that the subsidies for the acquisition of electric cars (i.e. SIN$20.000 per car) are given in time t=0, and that tax rebates for electric cars (i.e. SGD$ 100 in the first year; SGD$200 in the second year and SGD$350 from the third year on) are given for the 17 years' timeframe.

The EACs faced by the private sector are assumed to be composed of the non-subsidized acquisition costs for the ICE cars and EV cars and of the operational costs (maintenance, road tax, insurance and petrol/electricity).

Table 6: Equivalent Annual Costs for electric vehicles in the study site. Private sector costs, public sector costs and aggregated costs for BAU and each scenario.

	Unit	Method	Scenarios Electric vehicles (17 YEARS TIMEFRAME)					
			BAU	**S1**	**S2**	**S3**	**S4**	**S5**
Costs metrics			No Electric Vehicles	**33% of the fleet electrified** 66% of the fleet non-electrified	**66% of the fleet electrified** 33% of the fleet non-electrified	**100% of the fleet electrified**	**100% buses electrified** 100% of cars non-electrified	**100% cars electrified** 100% of buses non-electrified
Total Equivalent Annual Costs	SGD / yr	CityMos + post-analysis	**$44,215,000**	**$ 45,472,000**	**$ 47,150,000**	**$49,291,000**	**$44,481,000**	**$ 49,024,000**
Equivalent Annual Costs faced by the Government (buses +subsidies for E. Cars +infrastructure for E. cars)	SGD / yr	CityMos + post-analysis	$ 2,534,000	$ 5,285,000	$ 8,039,000	$10,872,000	-	-
1. Equivalent Annual Costs (only buses)	SGD / yr	CityMos + post-analysis	$ 2,534,000	$ 2,622,000	$ 2,712,000	$ 2,800,000	$ 2,800,000	$ 2,534,000
2. Equivalent Annual Costs (only subsidies for Electric cars +infrastructure for E. cars)	SGD / yr	CityMos + post-analysis	-	$ 2,663,000	$ 5,327,000	$8,071,000	-	$8,071,000
Equivalent Annual Costs faced by the Private Sector (only private cars expenditure)	SGD / yr	CityMos + post-analysis	$41,680,000	$40,187,000	$ 39,111,000	$38,418,000	$41,680,000	$ 38,418,000

Table 6 shows the total EAC for each of the scenarios evaluated for the study site (first line in Table 6). The EAC values increase progressively as the percentage of electrification of the fleet increases. The values increase by 2.84%, 6.64% and 11.48% in S1, S2 and S3 compared with the BAU scenario. The EAC increase sonly by 0.60% in the scenario S4 and by 10.88% in the scenario S5, both compared with the BAU scenario. Comparing the S3 and S5 scenarios (i.e., all vehicles electrified or only the cars electrified, respectively), we see that the difference between those two is only 0.6%.

Table 6 also displays the EAC values faced only by the government (line 2 in Table 6) and also those faced only by the private sector (line 5 in Table 6), both for each scenario.

However, for the analysis done in this study, we only discuss the total EAC, i.e. the total equivalent annualised costs faced by government and private households in the BAU and each urban heat reducing scenario.

5.1.2 Cost-effectiveness calculation

In this subsection, we apply the Cost-effectiveness calculation described in Section 4.1. By implementing this framework, we evaluate the cost-effectiveness of each scenario (i.e., S1 to S5) compared with the BAU scenario for the electrification of the vehicle fleet.

In the upper part of Table 7, we display the results from the costs metrics (i.e., total EAC) for the BAU scenario and for the alternative scenarios considered S1 to S5. We discussed the EAC estimations for BAU and each of the implementation scenarios in Section 5.1.1.

In the middle part of Table 7, we display the results from the benefit calculations, i.e., the PET values (as indicator for outdoor thermal comfort), the energy consumption and the greenhouse gas emissions. We display the results of each of these metrics for the BAU and per each implementation scenario (S1 to S5) (for more details see Adelia et al., 2020).

We observe that the lowest PET value is obtained by the implementation of a 100% electrification of the vehicle fleet. We observe a 0.91 C° decrease in PET in the respective scenario (i.e., S3), compared with the BAU scenario. We also see a 0.71 C° PET decrease in the scenario with only electrified buses (100%) (S4) and a 0.81 C° PET decrease in the scenario with only electrified cars (100%) (S5), both compared with the BAU scenario.

Table 7: Total EACs, benefits and CERs for the electric vehicles

	Unit	Scenarios Electric Vehicles					
		BAU	**S1**	**S2**	**S3**	**S4**	**S5**
		No Electric Vehicles	**33% of the fleet electrified** 66% of the fleet non-electrified	**66% of the fleet electrified** 33% of the fleet non-electrified	**100% of the fleet electrified**	**100% electric buses** 100% of cars non-electrified	**100% electric cars +** 100% bus non-electrified
Costs estimations							
Total Equivalent Annual Costs (EAC)	SGD / yr	$ 44,215,000	$ 45,472,000	$ 47,150,000	$ 49,291,000	$44,481,000	$ 49,024,000
Benefit estimations							
PET index (proxy for outdoor thermal comfort)	Degree C^0	37.22	36.91	36.61	36.31	36.51	36.42
Energy consumption	GWh/yr	68.9	53.4	37.7	22.8	53.7	37.6
Greenhouse gas emissions	kton CO2e/yr	17.35	16.03	12.32	9.55	13.82	13.01
Cost-Effectiveness Ratio (CER)							
CER PET value	-		$ 4,054,000	$ 4,811,000	$ 5,578,000	$ 374,000	$ 6,011,000

We also display the additional benefits that come along with the implementation of electric vehicles in the study site. In Table 7, we see that energy consumption and greenhouse gas emissions decrease significantly with the implementation of the different new technology scenarios. The more the fleet is electrified, the lower are the energy consumption and the greenhouse gas emissions. The reduction in energy consumption amounts to 66.91%, 22.01% and 45.43% for the scenarios S3, S4 and S5 respectively, compared with the BAU scenario.

The greenhouse gas emissions decrease with an increasing degree of fleet electrification. The 100% electrification scenario (S3) presents a 44.96% reduction in GHG emissions compared with the BAU scenario. If only 100% of the buses are electrified (S4) or only 100% of the private cars are electrified (S5), we obtain an emission reduction of 20.35% or 25.02% compared with the BAU scenario.

The bottom part of Table 7 reports the cost-effectiveness ratio (CER) calculated following Equation (3) in Section 4.2. The CER shows the costs, which have to be paid for a 1-degree C° reduction of the PET indicator compared with the BAU scenario. As the scenarios S1 – S5 present an improvement of the PET value at higher costs, those scenarios lie in the NE sector of Figure 2. This means that we should select scenarios that lie on the lowest gradient line.

In the last row of Table 7, we see that the CER increases as the percentage of the fleet electrification increases (from S1 to S3). The CER in the 100% fleet electrification scenario (S3) is 37.59% higher than in the 33% electrification scenario (S1).

Scenario S1 seems preferable as it presents a lower cost per 1-degree PET improvement. However, the picture changes if we consider the additional benefits that come with a higher degree of fleet electrification (for instance S3). As described above, scenario S3 brings a significant decrease in energy consumption and in greenhouse gas emissions compared with the BAU and S1 scenarios.

In the last row of Table 7, we also report the CER results for the electrification of buses only (S4) and the electrification of cars only (S5). We observe that the additional costs per degree of PET improvement are only SGD 374.000 in S4 compared with the BAU scenario. The total electrification of buses also brings a significant reduction in both energy conservation and greenhouse gas emissions. In the case in which only cars are electrified (S5), we observe a CER of around SGD 6m. The respective CER is higher than the CER resulting from the 100% fleet electrification (S3). This result suggests that it might be more preferable to electrify the entire fleet instead of electrifying cars only. This holds even more if the additional benefits are taken into account.

Overall, our results suggest that the electrification of buses only (S4) might be the most preferable scenario: it presents the lowest CER across all scenarios along with significant additional benefits for the environment, like a decrease in energy consumption and a decrease in greenhouse gas emissions compared with the BAU scenario.

The scenario that presents the highest improvement in OTC is the 100% electrification of the fleet (S3), but it comes with higher costs and a higher CER value. For S3, the reductions in energy consumption as well as in GHG emissions are the highest among S1 to S5. It seems recommendable to consider these benefits in addition to the CER value. Policy makers would need a weighting scheme for the three benefit metrics in order to make a rational choice of an urban heat mitigation measure.

5.2 District Cooling Systems

In this Subsection, we show the costs, benefits and cost-effectiveness calculations for District Cooling Systems. We display the results for different scenarios. More details about the District Cooling Systems, along with their Capex and Opex costs, can be found in the “Potential of District Cooling in Singapore: From Micro to Mesoscale” Technical Report from the Cooling Singapore project produced by Riegelbauer et al. (2020).

5.2.1 Costs

Assumptions about technologies

Following Riegelbauer et al., 2020, the cooling system of an area is a combination of three main sub-systems. These are the Conversion System, the Air-Conditioning System, and the Ventilation System. Table 8 and Table 9 indicate the type of technologies used per sub-system, scenario, and land-use in the study area. We also describe the type of technology used for centralized buildings (i.e., buildings that are connected to a central District Cooling System) and for decentralized buildings (i.e., buildings that are not connected to a central District Cooling System) (see Figure 4).

Figure 4: Schematic presentation of cooling systems' location (in red) in decentralized (left) and centralized (right) buildings in the study area.

The BAU scenario with respect to district cooling represents the most commonly used cooling systems of Singapore's building stock today. These cooling systems are decentralized per building and, as such, no district cooling schemes. For residential buildings, the BAU scenario's conversion system uses Direct Expansion Units (DEX) to reject heat into the outdoor environment. The air conditioning system uses a Fan coil or mini-split unit (FC), which is typical for residential units. The ventilation system consists of natural ventilation (NV).

On the other hand, for commercial buildings, the BAU scenario's conversion system consists of a combination of vapour compression chillers (VCC) and Wet cooling towers (WCT) to reject heat into the outdoor environment. The air conditioning system uses an air handling unit (AHU), typical for medium-size and large commercial units, including retail, hotels, and offices. The ventilation system consists of traditional mechanical ventilation with metallic ducting and electrical fans (MV).

At the side of the BAU scenario, we also consider 33%, 66% and 100% scenarios for district cooling. As before, we name them S1, S2 and S3. The 33% district cooling scenario portrays an integration of 33% of the buildings into a District Cooling System (DCS) (centralized) through a cold-water network.

The scenario includes a remaining 66% of the buildings using typical cooling systems as they are used in Singapore today. For both commercial and residential buildings connected to the centralized District Cooling System, the scenario's conversion system uses VCC and WCT, the air conditioning system uses AHU, and the ventilation system is MV. For commercial and residential buildings not connected to the District Cooling System (DCS) (decentralized), the cooling system is the same as described for the BAU scenario.

The 66% and 100% district cooling scenarios follow the same rationality of the 33% scenario regarding the cooling system technology and configurations.

Table 8: Technologies used in each scenario at the decentralized and centralized scales for Residential buildings.

	BAU	S1	S2	S3
	All cooling is decentralized	**DCS satisfies 33% of the cooling demand** 66% of all cooling decentralized	**DCS for 66% of cooling demand** 33% of all cooling decentralized	**DCS for 100% of cooling demand**
Conversion System Type	Central: - Decentral: DEX	Central: VCC + WCT Decentral: DEX	Central: VCC + WCT Decentral: DEX	Central: VCC + WCT Decentral: -
Air Conditioning System Type	Central: - Decentral: FC	Central: AHU Decentral: FC	Central: AHU Decentral: FC	Central: AHU Decentral: -
Ventilation System Type	Central: - Decentral: NV	Central: MV Decentral: NV	Central: MV Decentral: NV	Central: MV Decentral: -

DEX: Direct expansion unit. VCC: Vapour compression chiller. WCT: Wet cooling tower. FC: Fan coil mini-split unit. NV: Natural ventilation. MV: mechanical ventilation. AHU: air conditioning system uses an air handling unit.

Table 9: Technologies used in each scenario at the decentralized and centralized scales for Commercial buildings.

	BAU	S1	S2	S3
	All cooling is decentralized	**DCS satisfies 33% of the cooling demand** 66% of all cooling decentralized	**DCS for 66% of cooling demand** 33% of all cooling decentralized	**DCS for 100% of cooling demand**
Conversion System Type	Central: - Decentral: VCC + WCT	Central: VCC + WCT Decentral: VCC + WCT	Central: VCC + WCT Decentral: VCC + WCT	Central: VCC + WCT Decentral: VCC + WCT
Air Conditioning System Type	Central: - Decentral: AHU	Central: AHU Decentral: AHU	Central: AHU Decentral: AHU	Central: AHU Decentral: AHU
Ventilation System Type	Central: - Decentral: MV	Central: MV Decentral: MV	Central: MV Decentral: MV	Central: MV Decentral: MV

DEX: Direct expansion unit. VCC: Vapour compression chiller. WCT: Wet cooling tower. FC: Fan coil mini-split unit. NV: Natural ventilation. MV: mechanical ventilation. AHU: air conditioning system uses an air handling unit.

Assumptions about specific technology costs

Table 10 presents the specific costs and cost calculation parameters of the cooling systems analysed in this study. We follow a simplified approach, where the investment costs are defined per unit of thermal capacity installed. The costs include design fees, contingencies, and taxes (Riegelbauer et al, 2020 for more details of these cost items).

We are confronted with two types of investment costs for a decentralized cooling of buildings. The investment costs of the system 'VCC + WCT + AHU + MV for buildings that are cooled in a decentralized way comprise costs for vapour compression chillers, cooling towers, chilled water pumps, chilled water pipework, condenser water pumps, and condenser water pipework for the conversion component of the cooling system (see Riegelbauer et al, 2020). They further include a share of the centralized air conditioning system costs, namely the air handling unit, air conditioning ductwork, and automatic control works (see Riegelbauer et al, 2020 for more details).

The investment costs of the system 'DEX + FC + NV for buildings that are cooled in a decentralized way comprise costs for condenser units, indoor units, and piping. They do not include the costs of concealing piping, which is allocated to the inherent construction costs of building developers (see Riegelbauer et al, 2020).

Table 10: Specific costs per technology and cooling system.

Item	Specific Cost [SGD/kW]	Lifetime [LT]	O&M [%]	Discount Rate [%]	Source
VCC + WCT + AHU + MV for decentralized buildings	1170	20	4%	3%	(Arcadis 2016)
DEX + FC + NV For decentralized buildings	380	15	12%	3%	Retailer
VCC + WCT + NETWORK + MV For centralized buildings	2080	50	2%	3%	(ASHRAE, 2009 , Arcadis 2016)
ELECTRICITY For centralized and decentralized buildings	0.25/0.188*	-	-	-	EMA[2], OEM[3]

DEX: Direct expansion unit. VCC: Vapour compression chiller. WCT: Wet cooling tower. FC: Fan coil mini-split unit. NV: Natural ventilation. MV: mechanical ventilation. NETWORK: District Cooling network. ELECTRICITY: electricity.

* Cooling operators with a monthly electricity consumption above 2000 kWh/month are assumed to purchase electricity from the open electricity market, benefitting of reduced rates

[2] https://www.openelectricitymarket.sg/business/list-of-retailers#business-consumers-min-2000

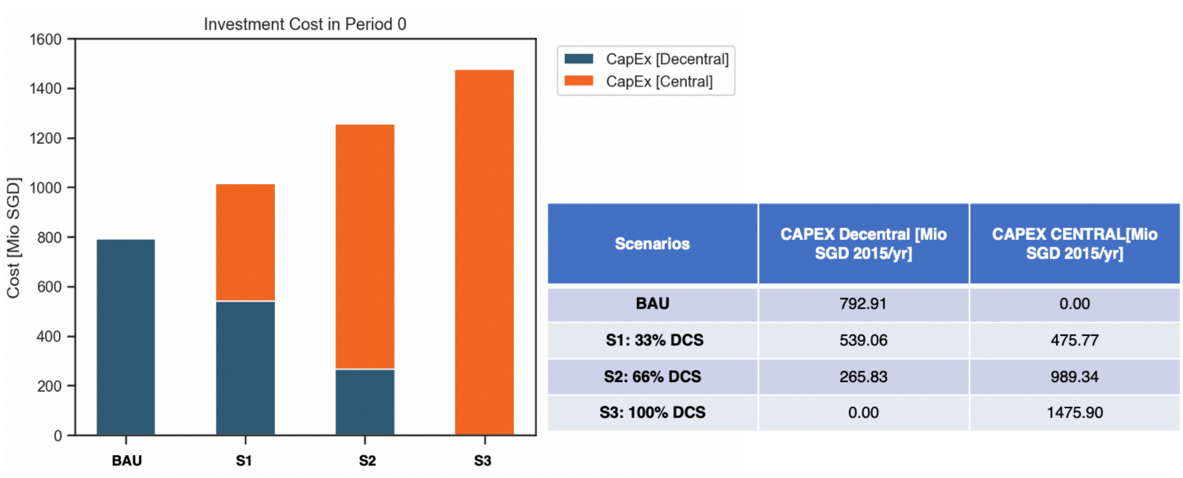
[3] https://iswitch.com.sg/singapore-electricity-prices/

The investment cost of the system ‘VCC + WCT + NETWORK + MV for buildings that are cooled in a centralized way, i.e. the district cooling system investment costs comprise costs for the District Cooling System, the district cooling network, energy transfer stations, and a share of the central air conditioning system of buildings. The lifetime of the entire system is estimated to be 50 years, even though single components might deviate (see Fonseca et al., 2020; Riegelbauer et al, 2020). This estimation is mainly due to the long-term duration of fixed investment components of the District Cooling Systems' infrastructure (i.e. district cooling network, energy transfer stations, and the central air conditioning systems of buildings) as declared by district cooling providers (Tabreed, 2018). The operational and maintenance percentage of the total costs amounts to 2% (Ashrae, 2009). It is low compared to decentralized cooling systems, which show a share of 22.8% for operational and maintenance costs compared to the total costs (see Riegelbauer et al, 2020).

Since all systems are electrically powered, the electricity price is pivotal in analysing the costs. In Singapore, large consumers with a monthly electricity consumption above 2000 kWh/month are allowed to purchase electricity from the open electricity market, benefitting from reduced rate [2]. We assume that all cooling operators, who meet this criterion, benefit of a 25% price reduction compared to the standard electricity tariff[3] (see Riegelbauer et al, 2020).

Investment costs

Regarding investment costs, we assume all cooling systems for our study area to be installed in period 0. A trend of increasing investment costs with an increasing share of buildings belonging to the district cooling system can be observed in Figure 5. Scenario S3, the scenario in which 100% of the cooling demand is satisfied by a centralized system, is the most capital intensive scenario (see Riegelbauer et al, 2020). The total capital expenditure amounts to approximately 1.48 billion SGD for the entire district cooling system, while cooling systems in the BAU scenario account for investment costs of 790 million SGD. Decisive for this gap is the investment for the district cooling network and the energy transfer stations (see Riegelbauer et al, 2020).



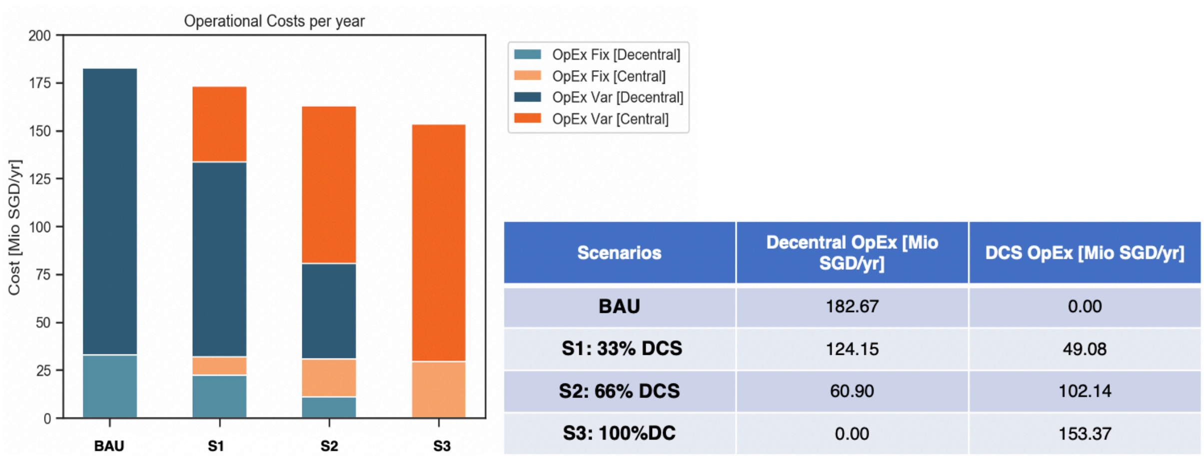
Scenarios	CAPEX Decentral [Mio SGD 2015/yr]	CAPEX CENTRAL[Mio SGD 2015/yr]
BAU	792.91	0.00
S1: 33% DCS	539.06	475.77
S2: 66% DCS	265.83	989.34
S3: 100% DCS	0.00	1475.90

Figure 5: *Investment costs for all scenarios (source: Riegelbauer et al., 2020).*

BAU: Business as usual scenario; S1: 33% district cooling scenario; S2: 66% district cooling scenario; S3: 100% district cooling scenario. CapEx [Decentral]: Investment or capital costs for locally cooled buildings. CapEx [Central]: Investment or capital costs for centrally cooled buildings.

Operational costs

For cooling systems, the operational or running costs per year decrease with an increase in the district cooling share (see Figure 6). This cost decrease can be attributed to the efficiency improvements of district cooling systems, which result in a lower electricity consumption of the cooling system (see Riegelbauer et al, 2020). For centralized cooling systems, the relative operational and maintenance costs are low, compared to buildings that are cooled in a decentralized way (see Riegelbauer et al, 2020).



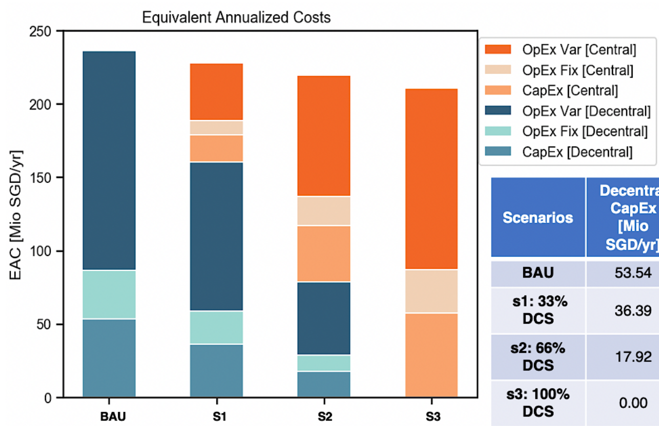
Scenarios	Decentral OpEx [Mio SGD/yr]	DCS OpEx [Mio SGD/yr]
BAU	182.67	0.00
S1: 33% DCS	124.15	49.08
S2: 66% DCS	60.90	102.14
S3: 100%DC	0.00	153.37

Figure 6: *Operational costs for all scenarios (source: Riegelbauer et al., 2020).*

BAU: Business as usual scenario. S1: 33% district cooling scenario. S2: 33% district cooling scenario. S3: 100% district cooling scenario. OPEX Fix [Decentral]: Fixed operational costs for locally cooled buildings. OPEX Fix [Central]: Fix operational costs for centrally cooled buildings. OPEX Var [Decentral]: Variable operational costs for locally cooled buildings. OPEX Var [Central]: Variable operational costs for centrally cooled buildings.

Equivalent Annual Costs

The equivalent annualized costs decrease with an increase in the district cooling share (see Figure 7). Operational costs are dominant within the annualized costs, resulting in central District Cooling Systems (DCS) being more profitable than decentralized cooling systems (see Riegelbauer et al, 2020). The 100% DCS scenario (S3) has annualized costs that are 11% lower than those of the BAU scenario, with a total EAC of 211 million SGD per year. This result implies that the implementation of a District Cooling System profits from economies of scale. The higher the share by which the cooling demand satisfied in a centralized way, the lower the equivalent annual costs to satisfy the respective cooling demand (see Riegelbauer et al, 2020 for more details on the costs estimations). As mentioned in Subsection 4.3, a 3% discount rate was used for the estimation of the EAC of a District Cooling System in the study area.



Scenarios	Decentral CapEx [Mio SGD/yr]	DCS CapEx [Mio SGD/yr]	Decentral OpEx [Mio SGD/yr]	DCS OpEx [Mio SGD/yr]	Decentral EAC [Mio SGD/yr]	DSC EAC [Mio SGD/yr]	EAC [Mio SGD/yr]
BAU	53.54	0.00	182.67	0.00	236.20	0.00	236.20
s1: 33% DCS	36.39	18.49	124.15	49.08	160.53	67.58	228.11
s2: 66% DCS	17.92	38.45	60.90	102.14	78.82	140.59	219.41
s3: 100% DCS	0.00	57.36	0.00	153.37	0.00	210.73	210.73

Figure 7: Equivalent annual costs (EAC) for all scenarios *(*source: *Riegelbauer et al., 2020).*
BAU: Business as usual scenario; S1: 33% district cooling scenario; S2: 66% district cooling scenario. S3: 100% district cooling scenario. OPEX Fix [Decentral]: Fixed operational costs for locally cooled buildings. OPEX Fix [Central]: Fix operational costs for centrally cooled buildings. OPEX Var [Decentral]: Variable operational costs for locally cooled buildings. OPEX Var [Central]: Variable operational costs for centrally cooled buildings. CAPEX [Decentral]: Investment or capital costs for locally cooled buildings. CAPEX [Central]: Investment or capital costs for centrally cooled buildings.

5.2.2 Cost-effectiveness calculation

In this Subsection, we apply the Cost-effectiveness calculation described in Section 4.1 for the District Cooling Systems. By implementing this framework, we evaluate the cost-effectiveness of each scenario (i.e., S1 to S3) in comparison with the BAU scenario for the DCS.

Similar to Table 7 in subsection 5.1.3, Table 11 shows the estimation results of the total EAC costs for the BAU scenario and for the urban heat reduction scenarios under consideration (S1 to S3) (see

Riegelbauer et al., 2020 for more details of the costs estimations for DCS). As discussed in Section 5.2.1, District Cooling Systems offer economies of scale with respect to the cooling purpose. Hence, the higher the share of centralized cooling, the lower the resulting equivalent annual costs. We see from table 11 that the EACs are lower for scenarios S1 to S3 compared to the BAU scenario. The difference is - 3.42% for S1; - 7.10% for S2 and; - 10.78% for S3. These results suggest that it might be preferable to cover 100% of the cooling demand by a District Cooling plant.

In the second part of Table 11, we display the benefits estimations. As for the electric vehicles, we consider the PET index, the energy consumption as well as greenhouse emissions for the BAU scenario and for every district cooling scenario. The energy consumption and the greenhouse emissions for all scenarios were estimated, while the PET index was estimated only for the BAU and the S3 scenario (i.e., for 100% district cooling) due to time constraints (see Adelia et al., 2020 for more details on the PET estimations). The PET values for the intermediate scenarios S1 and S2 were extrapolated, assuming a linear decrease in the PET values along with an increasing percentage of the cooling demand being satisfied in a centralized way (see Adelia et al., 2020). Our results suggest that for our study area, an increase in district cooling facilities has a positive impact on the reduction of urban heat. For the S3 scenario, the PET value is lower than for the BAU scenario and for S1. The difference between the BAU PET and the S3 PET, i.e., the PET value for 100% district cooling is - 1.1^{0}C.

Table 11: Costs, benefits and CERs for district cooling system

		Scenarios District Cooling Systems			
	Unit	**BAU**	**S1**	**S2**	**S3**
		All cooling is decentralized	**DCS satisfies 33% of the cooling demand** 66% of all cooling decentralized	**DCS for 66% of cooling demand** 33% of all cooling decentralized	**DCS for 100% of cooling demand**
Costs estimations					
Equivalent Annual Costs Total	SGD / yr	$ 236,200,000	$ 228,114,000	$ 219,420,000	$ 210,739,000
Benefit estimations					
PET index (proxy for outdoor thermal comfort)	Degree C^{0}	37.83	37.47	37.1	36.73
Energy consumption	GWh/yr	1928	1878	1824	1773
Greenhouse gas emissions	kton CO2e/yr	965	940	913	888
Cost-Effectiveness Ratio (CER)					
CER PET index	-		- $22,461,000	- $22,986,000	- $23,146,000

The middle part of Table 11 also shows the energy consumption and the greenhouse gas emissions estimation results related to the BAU scenario and the three district cooling scenarios (S1 to S3) (see Adelia et al., 2020 for more details of these estimations). We observe that energy consumption and the greenhouse gas emissions decrease significantly when moving from the BAU scenario over the S1 scenario to the S3 scenario. Both, energy consumption and greenhouse gas emissions decrease by 8% in the 100% district cooling scenario (S3) compared with the BAU.

In the last row of Table 11, we report the CER results (see more details related to the CER concept in Sections 4.2. and 4.5). As described in Section 4.2, we calculated the CER with respect to our key benefit, i.e., with respect to the PET value. Compared to the BAU scenario, the EAC and the PET values are decrease progressively as the percentage of district cooling demand increases in each of the district cooling scenarios (i.e., from S1 to S3). Hence, the district cooling scenarios S1 to S3 present win-win situations. Each of the district cooling scenarios dominates the BAU scenario, i.e. the "0 scenario" and lies in the SE sector of Figure 2. Therefore, all district cooling scenarios appear eligible to be implemented. S3 seems to be the most preferable scenario as this one presents the lowest CER across all scenarios. This means that a complete satisfaction of the cooling demand would give, compared to the BAU scenario, the lowest costs per reduction of 1-degree C in PET. Furthermore, this scenario also yields the highest additional benefits with respect to a decrease in energy consumption and greenhouse gas emissions.

6 Conclusions

6.1 Summary and assessment of findings

In this study, we evaluate the net benefits of two different heat mitigation technologies in a specific area in Singapore. Specifically, we analyse effects of an electrification of the vehicle fleet and of a district cooling system. The results from our study enable policymakers to decide whether to implement one of these two technologies in the study site. The methods we use offer the opportunity to assess the net benefit of other strategies to mitigate urban heat or to assess the implementation of heat reducing measures in other sites.

Typically, net benefit assessment are done using the framework of CBA. To perform CBAs, it is necessary to express all costs and benefits in monetary terms. However, a monetarization of the benefits resulting from a policy intervention is often hardly possible. In such cases, CEA can be used. They indicate the overall costs accruing from pre-defined improvements of one or several benefit indicators.

In our analysis, we implement a CEA to identify at which costs the electrification of the vehicle fleet or a district cooling system could improve the OTC of the local population to a specific degree. To operationalize our key benefit, i.e. the OTC, we use the Physiological Equivalent Temperature (PET) index. This index maps changes in the thermal environment of individuals. A decrease in PET can be interpreted as a proxy for an improvement in OTC. Besides, we consider additional benefits, i.e. a reduction in the final energy demand and a decrease in greenhouse gas emissions, caused by the two above-mentioned strategies to mitigate urban heat. Using our key benefit indicator, i.e. the PET, we calculate the CER for our Business-as-Usual (BAU) scenario as well as for all implementation scenarios of the two interventions we are looking at (electrification of vehicle fleet, district cooling system). The CER shows the lifespan costs needed for a temperature reduction of 1°C. Rules to make rational decisions on the choice of urban heat mitigation measures based on the CER indicator are discussed in chapter 4.

We evaluate the effects of different electrification and district cooling scenarios, varying the percentage by which the electrification or the district cooling system is completed. We compare the net-benefits of a 33%, 66% and 100% electrification of the vehicles fleet (compared to the BAU scenario) and the costs and benefits of a satisfaction of the cooling demand 33%, 66% and 100% coming from a district cooling system. Furthermore, we also study the net-benefits of scenarios in which only all buses or all private cars are electrified.

In case of electric vehicles, we observe that a higher degree of fleet electrification comes along with higher costs compared with the BAU scenario. However, the higher costs are accompanied by OTC improvements as well as by a reduced final energy consumption and reduced greenhouse gas emissions. In terms of net-benefits, the electrification of only 100% of the buses is shown to be the most preferable intervention. This scenario presents the lowest additional costs per 1-degree PET improvement compared with the BAU scenario. This scenario also brings a significant decrease of energy consumption and greenhouse emissions compared with the BAU scenario. Nevertheless, policy makers may decide to electrify the entire fleet, since this strategy results in the highest PET reduction (- 0.91°C). Besides, this scenario presents the lowest level of energy consumption and of greenhouse gas emissions compared to the BAU. Taking into account all those benefits, the full electrification might have the biggest positive impact on population health, productivity, cognitive performance and overall well-being.

With respect to district cooling as urban heat mitigation strategy, our findings show that a District Cooling System has not only a positive impact on OTC and comes along with lower costs than the BAU scenario. A District Cooling System also contributes to reducing the final energy consumption and the greenhouse gas emissions. The more the District Cooling System satisfied the energy demand, the lower the costs are due to economies of scale. Hence, it seems highly preferable to implement a District Cooling System and cover the entire cooling demand in the study area through this plant. This solution seems to yield the most favourable Cost-Effectiveness ratio.

In addition to the consideration of cost-effectiveness aspects, policy makers might consider the social acceptability of the different heat mitigation strategies. In this line, the estimation of residents' WTP could help to quantify the level of people's acceptance and support for the respective policy interventions. In Borzino et al. (2020), we assess the citizens' WTP for electric vehicles and District Cooling Systems in CBD and Punggol. We find a high level of support and acceptability of the implementation of these new technologies in both areas. Specifically, people in the CBD area seem to be willing to pay on average SGD 388 or SGD 385 per person to see District Cooling Systems or electric vehicles being introduced in their living areas.

Overall, we think that our study gives valuable insights into the costs and benefits of technological strategies to improve the OTC, to reduce the final energy consumption and to shrink the greenhouse gas emissions in Singapore. The evaluation of the net-benefits of the different scenarios has the potential to contribute to a more informed policymaking.

6.2 Limitations and next steps

A key limitation of our study was the small amount of time and financial resources. This hindered us from doing a full CBA, i.e. from quantifying in monetary terms not only the costs but also the benefits resulting from urban heat mitigation measures in our study area. The CBA analysis would allow us to map positive impact from heat reducing measures on health, productivity, cognitive performance, overall wellbeing and ultimately on the GDP. It seems worthwhile to aim for such a comprehensive analysis in order to make the choice of policy interventions more effective.

In addition, an extension of CEA or CBA from our study area to additional sites in Singapore should be aimed at. Furthermore, as mentioned above, an analysis to measure the societal support and the acceptance of different heat mitigation strategies would be important. The ultimate goals would be to develop a catalogue of heat mitigation measures ranked by their net-benefits in improving OTC, by other individual and aggregate indicators as those mentioned above, as well as by their level of societal support and acceptance. Based on such comprehensive information, policy makers would be able to make sustainable and welfare maximizing decisions in favour of their country.

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8 Appendix

Appendix 1

ELECTRIC VEHICLES:

Calculation of costs and assumptions

1. Electric buses

1.1. Acquisition costs

Obtained from the LTA tender documents.

S/No	Tenderer	Provision + Total Price
1.	BYD Singapore Pte. Ltd.	20 Single-deck buses S$17,246,317.00
2.	ST Engineering Land Systems *(Bidded as: Singapore Technologies Kinetics Ltd)*	20 Single-deck buses: S$15,148,400.00
3.	Yutong-NARI Consortium *(Bidded as: Zheng Zhou Yu Tong Bus Co., Ltd.)*	10 Single-deck buses & 10 Double-deck buses: S$18,246,523.70

Table 1: Costs of 10 EV and ICE double-deck and single deck buses. Tender 2018. Expected delivery between 2019-20. (Source: LTA)

A lifecycle of 17 years was used in the Total costs of ownership (TCO) analysis for buses because LTA vehicle registration expires after 17 years and buses cease operation after the registration expiry. Because there is no Singapore Consumer Price Index (CPI) prediction after the year 2023 an inflation rate of 1.9%, as suggested by the Monetary Authority of Singapore, was used to estimate the CPI.

From LTA tender, we calculated the acquisition costs for a 12 m double-deck and 12m single deck ICE and EV (table 2):

	BAU	**STRATEGY**
	normal combustion engine	**electric buses**
Acquisition costs (X UNIT 12m Double-Deck). Lifespan: 17 years	$ 741,000.00	$ 967,000.00
Acquisition costs (x UNIT 12m Single-Deck). Lifespan: 17 years	$ 550,000.00	$ 757,000.00

Table 2: acquisition costs of buses.

1.2. Charging Infrastructure costs

While the refuelling process of conventional combustion engine vehicles is fast and convenient today, charging of an EV remains more onerous, in locating a charging station and the duration of charging required. Unlike conventional fuels which requires minutes to refuel, batteries require relatively long charging times based on existing battery technology (current fast-charging of battery to 80% requires

20-30 minutes depending on the battery size, and slow-charging usually takes 4-7 hours). Hence, one of key challenges to higher take-ups of EVs is linked to the deployment of charging infrastructure.

There are different technologies to charge / transfer electrical energy to on-board energy storage systems (batteries or super capacitors) such as through wired/plug-in charging, battery swapping, flash charging and wireless/induction charging (Figure 1).

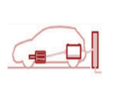
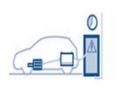
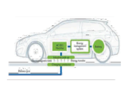
Charging concept	Plug-in slow charging	Plug-in fast charging	Inductive charging	Battery swapping
				
Description	Charge with cable while parked	Charged with cable while parked	Charged wirelessly	Drained batteries are replaced with freshly charged ones at swapping stations
Advantages	Low power Cheap Long charging time	High power Charging times in 10 – 30min Extends driving range	High convenience	Takes 5 minutes Unlimited driving range
Challenges	Takes 3 to 12 hours Limited driving range	High power Expensive	Expensive Low efficiency	Requires extra batteries Cost intensive system
Efficiency	96%	94%	91%	Depend on internal changing method use
Deploy-ment area	Personal in-house overnight charging	Public (car park near express way, office building ....)	Short, rapid charge area (ex: shopping mall)	Highway road, serving far travel-ling vehicles

Figure 1: Overview of charging concepts and features (Source: ERI@N)

Figure 2 illustrates the variety of factors which influence the costs associated with the installation of charging stations in Singapore. The varying site conditions result in broad price spans, when it comes to installation costs.

Selected impact factors on installation costs for charging infrastructure at parking sites

Impact Factor	Cost Influence	HDB Carparks	URA Carparks	Company Buildings and Shopping Malls
Distance to the next Power Source	Impacts length of cable and associated works	Substation next to carpark (up to few 100m of cable)	Distance to next substation varies (up to few km of cable)	Site dependent
General size of electrical package of building	A bigger size may have more capacity left for additional charging stations	In general provide a minimum level of power	In general provide a minimum level of power	In general bigger electrical package
Possibility to install charging stations inside	Less need for safety equipment, weather-proofing	In general multi-story carparks	Open-air carparks and road-side parking	In general multi-story carparks
Need for earthworks	Earthworks are labor and therefore cost-intensive	Less need due to inside installations, walls can be used	Earthworks needed as installations are outside	Less need due to inside installations
Number of stakeholders (agencies) to be consulted	The more parties involved the higher the costs	Experiences show long coordination efforts	Experiences show very long coordination efforts	Usually low coordination effort
Long-term usage of location	In a fast changing built environment land might be designated to new purposes	In general not affected from redevelopment	Located on state land could be taken up for redevelopment	In general not affected from redevelopment
Visibility of charging stations	Visibility of charging stations at highly frequented spots might increase usage	Low visibility due to inside installation	High visibility due to locations of open-air carparks	High visibility at work places and points of attraction

Main cost source | More favourable conditions | Less favourable conditions

Figure 2: Selected factors that influence the costs charging station installations[4] (Source: ERI@N, 2017)

Charging technologies calculations comprise conductive and inductive solutions which are currently common on the market (conductive solutions) and might become market ready in future (inductive solutions). Table 3 lists the charging technologies and the respective characteristics.

[4] The analysis in Eri@n (2017) was based on interviews with electromobility stakeholders in Singapore.

Charging Technology	Power Levels (kW)	Efficiency (%)	Power capacity per day (kWh)	Time for one charge (hours)	Lifetime (years)
AC Slow, Type 1, Single Phase	3.3	95	75.2	7.6	5
AC Medium, Type 2, Single Phase	6.6	90	142.6	3.8	5
AC Fast, Type 2, 3-Phase	44.0	90	950.4	0.6	5
DC Fast Charging	**50.0**	**90**	**1,080.0**	**0.5**	**5**
Inductive Charging, slow	3.3	87	68.9	7.6	5
Inductive Charging, fast	50.0	85	1,020.0	0.5	5

Table 3: Charging technologies and their characteristics (Source: ERI@N)

We use average prices for networked charging station solutions, provided by local charging infrastructure providers (ERI@N, (Figure 6)). Costs are expected to fall dramatically with achieved economies of scale due to globally rising demand for charging infrastructure (-5% in the calculation tool). Especially costs for AC Fast and DC charging stations are expected to fall radically. The current available DC options in Singapore come with a price tag of S$ 52,000, while companies publish already near-term target prices of US$ 6,500 (~S$ 9,000). Installation costs vary heavily from site to site in Singapore as well as in other cities (see Table 4). The main cost driver here is the distance to the power source. Installation costs are expected to decrease as future charging sites will be built with appropriate electrical infrastructure required to install charging stations (see Table 5).

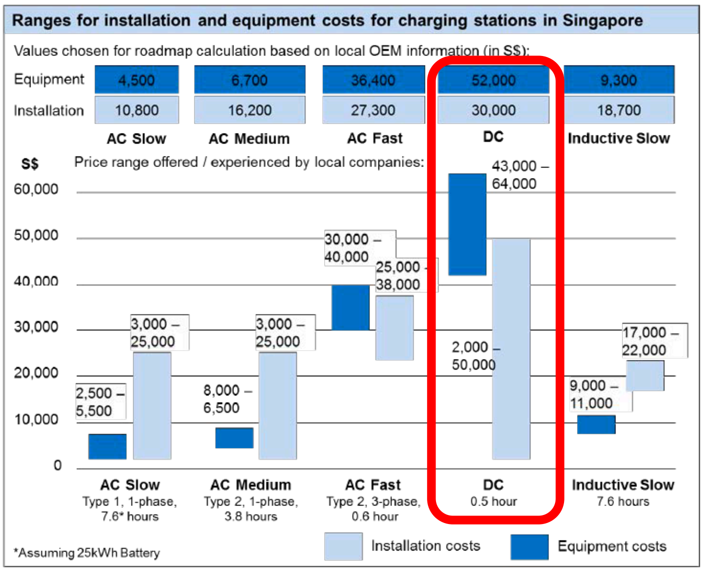


Figure 6: Ranges for installation and equipment costs for charging stations in Singapore. DC technology is the one assumed to be implemented in our CBA. (Source: ERI@N, 2017)

Table 4: Equipment, installation and operational costs per charging station and annual change rates

Charging Technology	Equipment Costs (EC) 2020 (S$)	Annual Change Rate EC	Install. Costs (IC) 2020 (S$)	Annual Change Rate IC	Operational Costs (OC) 2020 (S$)	Annual Change Rate OC
AC Slow	4,500	-5.0%	10,815	-3.0%	534	0.1%
AC Medium	6,750		16,223		561	
AC Fast	36,455	manually	27,350		617	
DC	**52,000**		**30,000**		**614**	
Inductive Slow	9,347	-5.0%	18,694		534	
Inductive Fast	18,694		37,388		534	

(Source: ERI@N, 2017)

Table 5: Costs for single charging station over time

	2020			**2030**			**2040**			**2050**		
Charging Technology Costs (S$)	EC	IC	OC	EC	IC	OC	EC	IC	OC	EC	IC	OC
AC Slow	4,500	10,815	534	3,482	9,287	537	2,085	6,849	542	747	3,724	553
AC Medium	6,750	16,223	561	5,223	13,931	564	3,127	10,273	569	1,121	5,586	581
AC Fast	36,455	27,350	617	24,027	23,486	620	4,000	17,319	626	2,000	9,418	639
DC	**52,000**	**30,000**	**614**	**25,000**	**25,762**	**617**	**4,000**	**18,998**	**624**	**2,000**	**10,331**	**636**
Inductive Slow	9,347	18,694	534	7,233	16,053	537	4,330	11,838	542	1,552	6,438	553
Inductive Fast	18,694	37,388	534	14,465	32,107	537	8,661	23,676	542	3,105	12,875	553

(Source ERI@N, 2017)

1.3. Operational Costs

The operating costs assessed included the road tax, energy costs, maintenance costs, cleaning costs, and personnel costs. The operating costs are calculated for the period of 17 years.

The operational characteristics of the current bus system as well as the Electric Buses system are given in Table 6. In our simulation inputs, the distance travelled per bus is 324.5 km. Buses cannot be used 10% of the year due to preventive and unscheduled maintenance (LTA, 2017). Because the down time of EVs due to maintenance is shown to be 50% of those of ICE vehicles (Mitropoulos et al., 2017), it was assumed that the electric buses are used 95% of the year. For comparison purposes, the ICEV is assumed to have identical daily operation schedules as the EV, but require identical maintenance time to conventional buses. Current buses operate with an average occupancy of 17% (LTA, 2017). The same rate of occupancy was estimated for the Electric buses.

Parameters	12 m buses- ECI	12 m buses EV
Average days of operation per year	329	347
Average distance travelled /day, km	324.5	324.5
Annual use, days	329	347

Table 6: Simulation inputs. Operational characteristics of buses.

In the operating costs, we include the road tax, energy costs, maintenance costs, insurance costs, cleaning costs, and bus captain costs for the 12 m double-deck (DD) ICE buses and EV discounted to the year 2020. The analysis period is between 2020 and 2037. All the operating costs shown are discounted to their 2020 values. The EOL cost for the EV was included as a negative cost in the maintenance costs. Table 7 shows the share of the operational costs per item.

	Operation costs	
	ICE buses (in %)	**Electric Vehicles (in %)**
Bus captain cost + cleaning costs	55.00	61.20
Insurance costs	6.00	6.00
Maintenance costs*	16.00	10.00
Energy costs	21.00	21.00
Road Tax	2.00	1.80
Total	*100.00*	*100.00*

Table 7: comparison of the operational cost shares for ICE and EV. *EOL value is included as a negative maintenance cost for EV

1.4. Road Tax

Road tax is a 6-monthly tax applicable for all transit buses registered in Singapore. The tax amount for each vehicle was estimated based on the engine type and maximum laden vehicle weight (LTA, 2017). The 2017 road taxes buses were estimated as S$1324 for the EV which fall under the category "Green, 20-26 tons" and S$1530 for buses which fall under the category "Diesel, 20–26 tons" (LTA, 2017). 2017 road taxes specified for buses increased by the CPI to estimate the taxes for the years 2030 and beyond.

1.5. Energy Costs

The annual electricity costs for the EV were calculated as function of the daily hours of operation, electricity consumption of the vehicle, efficiency of the charging station, and electricity prices. The hourly electricity consumption for the EV is 24.7 kWh (Chang et al., 2018; Teichert, 2017). The commercial electricity price was estimated applying the forecasted average change in the natural gas price in Europe, Japan, and the US (World Bank, 2018) to the 2017 value of the commercial electricity price (SP group, 2018) as mainly natural gas is used to generate electricity in Singapore. The charging station efficiency was estimated as 95%.

The fuel costs were calculated as a function of the daily distances travelled, diesel prices, and diesel consumption per vehicle. The fuel consumption of single-deck buses and double-deck buses are 0.51 L/km and 0.65 L/km, respectively (LTA, 2017). The bus depot diesel price in 2030 was estimated applying the forecasted change in the crude oil prices (World Bank, 2018) to the 2017 diesel price (Kochhan, 2017). The average daily operating time of the vehicles was estimated based on Table 6.

1.6. Maintenance Costs

Maintenance costs for buses and the ICE consist mainly of the service costs and overhaul costs for transmission and engine; while for EVs, they are mainly the battery replacement and service costs. LTA specifies a mid-life refurbishment on the 7th to 9th year of the bus registration that encompasses the engine overhaul as well as the refurbishment of the interior fittings (LTA, 2017). In this analysis, overhaul costs were calculated based on the U.S. DOT Volpe bus lifecycle cost model (USDOT Volpe Centre, 2018). However, the service costs were adjusted to account for differences in labour costs in Singapore (Payscale Singapore, 2018; Payscale US, 2018). The service costs for EVs were estimated as half of those of the ICE vehicles (Lai et al., 2013).

1.7. Insurance Costs

It is illegal to drive any vehicle in Singapore without valid vehicle insurance. The minimum requirement is to cover at least third-party liability for death and bodily injury arising from the use of the vehicle. The insurance costs of 12 m single-deck buses were estimated from the transit operations annual reports (SBS Transit, 2017). The insurance costs for the 12 m double-deck bus vehicles were obtained by scaling the 12 m single-deck insurance costs by the acquisition costs.

1.8. Cleaning Costs

The average service line time for cleaning is generally around 15 minutes per bus and buses are usually cleaned once a day (Schiavone, 2017). The Ministry of Manpower (MOM) of Singapore recommends a minimum monthly salary of S$1,200 for cleaners starting from 2019 (MOM, 2017). It was assumed that the vehicles are cleaned only the days when they are operating. The service line time of 15 minutes was used for 12 m buses and then scaled by the vehicle floor size for the double-deck buses.

It is assumed that the vehicles are cleaned only the days when they are operating, and the cleaning time required is proportional to the vehicle floor size. Singapore applies Progressive Wage Model for the low-wage earners including the cleaning sector (MOM, 2017).
However, there is no monthly minimum salary defined by MOM of Singapore after the year of 2019. Therefore, the wages for the years beyond 2019 were adjusted using the CPI. Personnel costs 2017 bus captain salaries increased by the CPI for the years 2030 and beyond.

1.9. Personnel Costs

According to the LTA, 1.8 bus captains are required on average to operate each bus. A bus captain salary of S$3500 (in 2017) was used in the analysis (LTA, 2017). Personnel costs 2017 bus captain salaries increased by the CPI for the years 2030 and beyond.

1.10. End-of-life (EOL) Costs

Public transportation buses are scrapped at the end of their 17 years lifetime (LTA, 2017). In the EOL cost calculations, it is assumed that the revenue of selling vehicle scrap material would be equal to the costs of scrapping. Therefore, no EOL value was assigned to ICE vehicles. However, for the EV, the batteries are replaced when the remaining maximum battery capacity reaches 70–80% of its original value (Teichert, 2017). Therefore, remaining battery value was added as a negative cost to the operational costs for the years when the battery is replaced. It is assumed that the price for the second-life batteries with 70–80% of its original capacity would be 50% of the new battery.

It was assumed that the revenue of selling vehicle scrap material from vehicle components would be equal to the costs of scrapping. However, for the EVs, remaining battery value was added as a negative cost to the operational costs for the years when the battery is replaced. It was assumed that the price for the second-life batteries with 70–80% of its original capacity would be 50% of the new battery. The estimated 2030 battery costs increased by the CPI for the years beyond 2030 (Monetary Authority of Singapore, 2018).

2. Costs for private cars

2.1. Costs for the Government

After declaring its ambition to phase out internal combustion engine (ICE) vehicles by 2040, Singapore will make electric vehicles more attractive from 2021. The Singapore Budget 2020 contemplates:

a. *the Vehicular Emissions Scheme, which metes out tax rebates and surcharges based on a vehicle's emission levels, will be extended to light commercial vehicles.*
b. *an early-adoption incentive scheme will be rolled out for EV buyers from 2021 to 2023. It will offer rebates capped at $20,000 per vehicle.*
c. *the road tax for EVs and some hybrids will be revised to be less punitive.*
d. *Singapore will expand the EV charging infrastructure significantly from 1,600 points now to 28,000 by 2030.*
e. *But as excise duty from fuel sales contributes around $1 billion a year, the Government will introduce a lump sum tax for EVs from 2021, starting at $100, then $200 in 2022, and $350 from 2023 onwards.*

For this analysis, we will assume that the number of private electric vehicles will be following each of our scenarios: BAU (0%); 33% (33% of the vehicles electrified); 66% (66% of vehicles electrified) and 100% (100% of vehicles electrified). We will assume that the subsidies will be received only once by the private agent and this agent will get the tax rebates for the whole period of our analysis.

2.2. Costs for the private sector

In our simulations, we consider the Toyota Corolla Altis (as ICE) and Nissan Leaf Electric (as EV).
We assume that the cars are bought in cash in time 0 and so, there is no interest to be paid for the loan. Electric cars cost less to maintain than their petrol counterparts (see Table 8). As they only need service for tyre rotation and brake fluid, maintenance costs are cheaper. A fully charged Nissan Leaf can go 150km, and it costs about $5 to fully charge the car's electric battery, which adds up to about $750 a year.

	Toyota Corolla Altis 1.6	Nissan Leaf Electric 24kWh
Fuel Economy	16.3km/litre	–
Energy Consumption	–	17.8kWh/100km (for driving in the city)
Petrol /electricity costs (in 1 year)	$1,639.26	

Table 8: petrol/ energy consumption of cars

2.2.1. Insurance costs

How much you need to pay in annual insurance premiums depends on a variety of factors that insurance companies consider pertinent to the risk you pose. These factors can include characteristics such as gender, age, driving experience, qualification for No Claim Discount (NCD) and occupation. Taking into consideration Singapore's most popular insurance companies, a Singaporean would expect to pay on average S$1,473 a year.

2.2.2. Maintenance costs

For reference, servicing a Toyota Corolla Altis would cost about S$621 over the course of one year for two servicing appointments. Maintenance is recommended either every 10,000 kms driven or every 6 months, whichever comes first. Most Singaporeans drive under 20,000 kms per year, so for the average driver it will likely be the latter. For electric vehicles the maintenance costs are significantly lower estimated at $200 per year.

2.2.3. Road tax

The amount of road tax you pay depends on the engine capacity of the vehicle (see Table 9) . The bigger the engine, the higher road tax. The rad tax can be estimated using a road tax calculator (ex Sgcarmart). The road tax for petrol-using vehicles is calculated as follows:

Engine Capacity (EC) in cc	Road Tax For 6 Months
EC < 600	$156.4
600 < EC < 1,000	S$156.4~S$195.5 or [S$200 + S$0.125(EC - 600)] x 0.782
1,000 < EC < 1,600	S$195.8~S$371.5 or [S$250 + S$0.375(EC - 1,000)] x 0.782
1,600 < EC < 3,000	S$372~S$1,192.6 or [S$475 + S$0.75(EC - 1,600)] x 0.782
EC > 3,000	>S$1,193.3 or [S$1,525 + S$1(EC - 3000)] x 0.782

Table 9: Engine capacity and road tax (Source: LTA)