Environmental performance of carsharing systems: the impacts of vehicle electrification, lifetime turnover and reuse

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SHORT SUMMARY

Several research has documented carhsaring's benefits; however, such benefits have been demonstrated looking at it as a static system and therefore not taking into account the quick turnaround of the vehicles and reuse of former carsharing vehicles. In this case, the environmental contirbution of carsharing is unclear. With the trend of electrification, the negligence of vehicle turnover and reuse can pose uncertainty on electric carsharing's contribution. This paper uses an agent-based modelling with life cycle assessment to examine the environmental impact of individual travel behaviour, operator's fleet management, and second life of former carsharing vehicles. Findings suggest that carsharing can reduce greenhouse gas (GHG) emission by 20% at vehicle level. With electric carsharing, it further reduces 55% more. At scenario level, results suggest that carsharing members can reduce GHG emissions by 12% upon joining carsharing. This saving is attributable to vehicle reuse, car ownership reduction, and fuel efficiency improvement.

Keywords: Carsharing, Electric vehicles, life cycle assessment, Agent-based, environment.

INTRODUCTION

Carsharing has recently emerged as an appealing alternative to the private car. For users, carsharing can be a flexible and cheap travel alternative to the private car. For cities, carsharing can help reduce the car dependency (Shaheen & Cohen, 2007, 2012; Chen & Kockelman, 2016), and several issues: GHG emissions, air pollution, noise, health problems, or land-use consumption (Shaheen & Cohen, 2007, 2012; Martin & Shaheen, 2011; Chen & Kockelman, 2016; Ding, Pan, Zhang, & Yang, 2019; Mont, 2004). These benefits can be even more substantial with electric shared vehicles (EVs). Although such benefits have been documented, the assessment of the global environmental impacts of carsharing and electric carsharing are still scarce. In general, one important issue relates to the fact that such benefits have been demonstrated looking at it as a static system and therefore not taking into account the quick turnaround of the vehicles. For example, after two or three years in service, carsharing fleet needs to be renewed due to intensive vehicle utilization or fleet management strategy (e.g., avoid increasing maintenance costs and value depreciation and to attract new members by introducing modern and efficient cars) (Mont, 2004; Rodrigues, 2018). (Chen & Kockelman, 2016; Best & Hasenheit, 2018) pointed out to the fuel efficiency improvement due to quick penetration of newer and cleaner vehicles in carsharing fleet; however, their studies did not quantify the physical and energy resource use for the vehicle turnover. In this case, the environmental impacts of carsharing is unclear. With electrification, frequent charging and fast charging together can also shorten lifespan of battery (Tomaszewska et al., 2019), thereby resulting in a replacement of battery or vehicle. Given this, the contribution of electric carsharing can be questionable. Further, after fleet renewal, former carsharing vehicles are typically sold to second-hand market to delay frequent vehicle scrapping, which is highly sensitive for environment (Guyon, 2017). To date, literature on vehicle reuse is sparse, as it is often overlooked; thus, several consequences remain unknown. To fill this gap, this research investigates the environmental impacts of carsharing electrification, turnover (replacement frequency), and reuse on second-hand market. Unlike previous research (Guyon, 2017), we investigate these impacts in a complex urban mobility system that includes carsharing, among other travel modes (private vehicles, transit, bikes, etc.). We also consider the heterogeneity of travelers and their preferences using an agent-based model.

METHODOLOGY

To assess the environmental impacts of carsharing in a complex urban mobility system, we combine an agent-based transportation model (ABM), namely *MATSim* (Horni, Nagel, & Axhausen, 2016) with a life cycle assessment (LCA) model (Sacchi, Mutel, Bauer, & Cox, 2019), as shown in (Figure 1). This methodology captures individual travel behavior, carsharing management and operation, vehicle reuse and their life cycle impacts. MATSim simulates daily urban mobility dynamics including carsharing and feeds its outcomes to the LCA model (*Carculator*). These outcomes include travel modes, travel times and distances, energy use for every agent. *Carculator* quantifies the environmental footprint of the private cars and carsharing by breaking down these impacts into different life stages to capture the whole range of impacts, beyond the scope of vehicle use. This methodology is applied to the case study of Montreal, Canada.

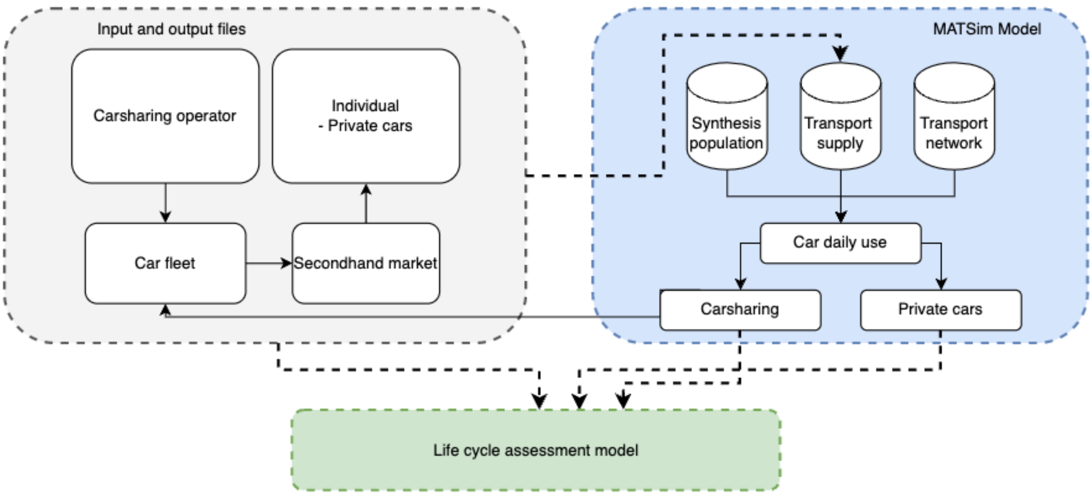

Figure 1: Simplified structure of ABM-LCA framework

Agent-based transportation model

MATSim is a multi-agent transportation and activity-based simulation framework (Horni et al., 2016). It simulates individual mobility behavior on a daily basis. MATSim agents perform activities, like work, education, or shopping. To engage in these activities, agents need to make different travel decisions: mode choice, departure time choice, or route choice. MATSim is capable of considering all these decision dimensions to maximize the utility of agents. To this end, it uses a co-evolutionary algorithm. That is, agents try out and score various travel choices, until an optimum is reached for each agent and for all the population.

Travel demand and supply: MATSim relies on a synthetic population of agents that replicates observed data on travel and activity habits of the population of interest. We adapt the synthetic population from (Manout & Ciari, 2021). This population includes main activities and travel characteristics of Montrealers.

For agents to perform their daily activities, they need to travel from one location to another. Travel can be performed using different travel modes: private car, transit, bike, walk, or carsharing. The supply of each mode is described in detail (networks, schedules, capacities, etc.). For carsharing, we include the location of stations, their number of vehicles, and their type (one-way or two-way).

Development of carsharing: To simulate the carsharing mobility scenario (including e-carsharing), we combine two MATSim extensions: carsharing (Ciari, Balac, & Axhausen, 2016) and electric vehicles (Waraich & Bischoff, 2016). Two types of electric shared cars are modeled:

1. One-way cars: cars can be picked up at a station and dropped-off at another one.
2. Two-way cars: cars can be picked up at any station but should be returned to the same station.

The use of shared EVs is constrained by their battery state-of-charge (SOC). The SOC of EVs decreases due to driving and to the use of auxiliary energy. The energy consumption of EVs is modelled according to (Bartlomiej, Slaski, & Maciejewski, 2016; Waraich & Bischoff, 2016).

Stations are located in areas with a high car trip production density, i.e. more than 60 outgoing car trips per day. This results in 568 stations for the Island of Montreal. In each station, at least 4 shared vehicles are available for reservation: 2 one-way and 2 two-way cars. The number of vehicles is proportional to the density of car trips. The fleet size of carsharing is 3,183 vehicles, 50% of which are EVs and the rest ICEVs (internal-combustion engine vehicles). EVs batteries have a capacity of 30 kWh. The recharging of shared EVs is only allowed at carsharing stations. Each station provides a charging infrastructure of 7.5 kW (Level 2 chargers).

Carsharing membership is sensitive to the accessibility of the system. In this research, we grant a carsharing membership to agents with a driving license and who live near a carsharing station, i.e. less than 500 meters.

Assumptions: Research on EVs highlights the impact of range anxiety on the adoption and use of battery-EVs (Franke, Neumann, Bühler, Cocron, & Krems, 2011; Franke & Krems, 2013; Tate, Harpster, & Savagian, 2008). Range anxiety can be defined as the fear of being stranded due to an empty EV battery (Tate et al., 2008). To include this effect in the simulation, we consider range anxiety as a penalty in the utility function of agents each time the state-of-charge (SOC) of the battery drops below a symbolic threshold of 10%. Consequently, agents learn to avoid using shared EVs in the case where it is likely for them to end up with a very low SOC. Further, the energy consumption of EVs depends on temperature (Bartlomiej et al., 2016; Yuksel & Michalek, 2015). We assume a constant temperature of 15°C.

Life cycle assessment

The system boundary in this LCA includes raw material extraction, vehicle operation and maintenance, end-of-life stage, fuel cycle, and infrastructure provision and maintenance. The functional unit is **the impacts of carsharing scenario in Montreal over 10 years**. 10 years is a reasonable lifetime for private cars and a convenient time frame to study mid-term impacts of fleet replacement strategies of carsharing operators. In this study, we limit the analysis of LCA results to greenhouse gas (GHG) emission. ReCiPe midpoint was used for the characterization method. Our inventory relied on *Ecoinvent 3.6*. Vehicle lifetime mileage (VLM) is assumed to be 150,000 km for private car (ICEV). This is derived from the annual mileage and vehicle age in Quebec (Natural Resources Canada, 2021). The VLM of shared vehicles is assumed to be 200,000 km for both ICEV and EV. This assumption is conservative considering that shared vehicle lifetime usually exceeds those of private cars and even taxi (Fernando et al., 2020). The electricity mix is modeled after the grid system of the province of Quebec, in which 99.8% of generated electricity is from hydro-power and wind (Canada Energy Regulator, 2021).

Quantification of vehicle turnover and reuse: To explore the impacts of vehicle turnover, we assume that carsharing vehicles' first useful lifespan is 3 years. After that, these vehicles are sold in the second-hand market. Further, these vehicles are assumed to reach the same lifetime mileage as their counterparts, private cars. These vehicles are also expected to have a total useful life of only 7 years compared to 10 years for private vehicles (Figure 2). To account for the impacts of vehicle turnover, we assume that (i) the production of new cars increases physical and energy resource use (negative impact), (ii) newly introduced vehicles are more fuel-efficient than old ones (positive impact) at each turnover and (iii) old shared cars are reused in the second-hand market (positive impact). The life cycle impacts of shared vehicles are split between the carsharing operator and private households. The allocation method is based on average carsharing and second-hand use annual mileage (Guyon, 2017).

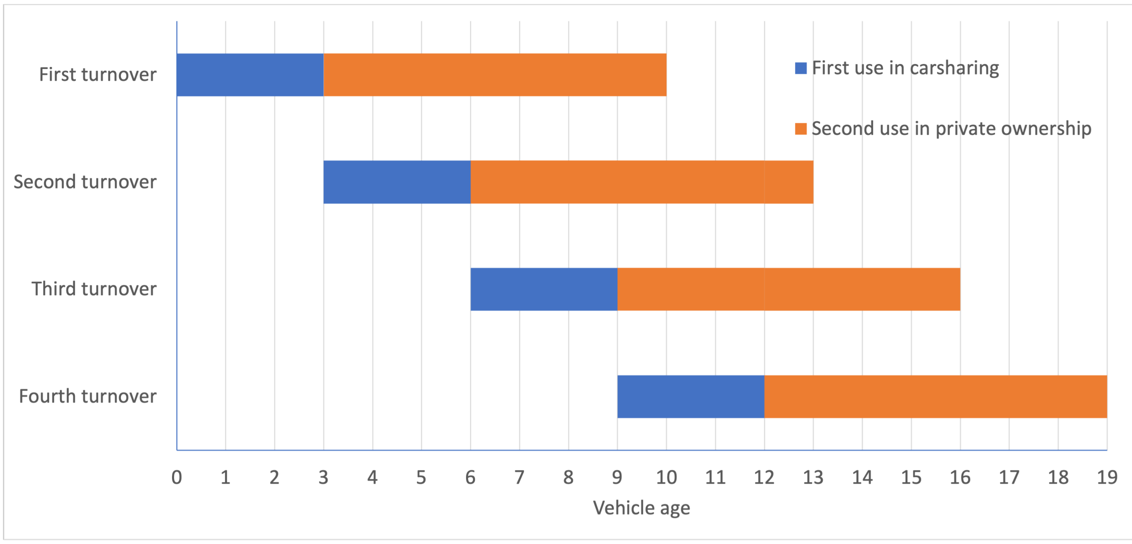

Figure 2: Fleet turnover at 3 years

RESULTS AND DISCUSSION

Results are described at both vehicle and scenario level. At the vehicle level, shared use vehicles have lower impact on all considered phases in comparison with private cars (Figure 3). This saving is attributable to the longer designed lifetime of carsharing and vehicle reuse. Shared ICEVs are found to reduce GHG emissions by 20%, while shared EVs at 75% compared to private ICEVs if the vehicle is produced in 2021. In addition, the result is sensitive to the vehicle production year, taking into account the changes in fuel economy, vehicle curb mass, infrastructure, etc. For example, the manufacturing and end-of-life impacts of shared EVs are shown to decrease over time; however, this reduction is offset by an increase in infrastructure impacts in the future.

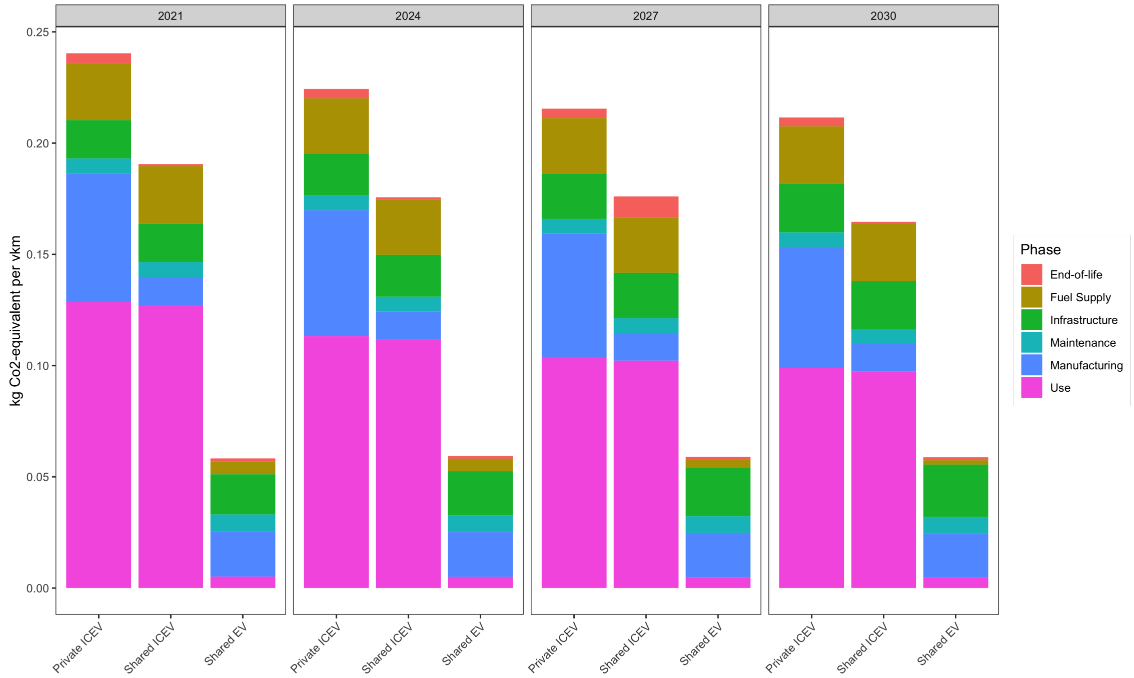

Figure 3: GHG impact at vehicle level

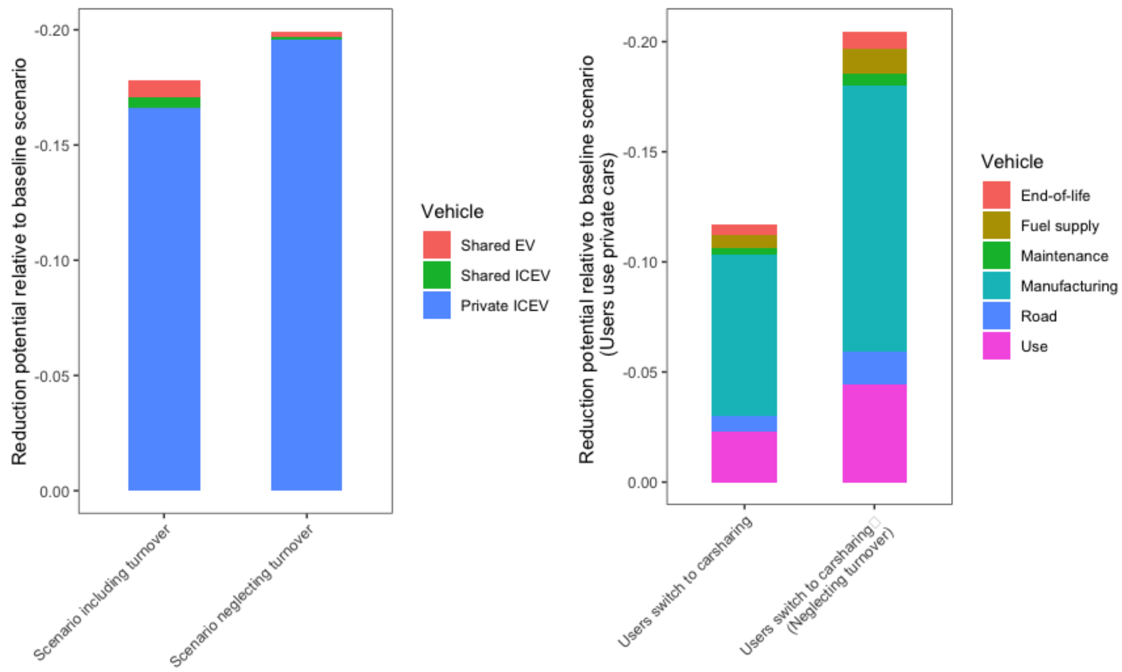

Figure 4: GHG impacts at scenario level (Left - Comparison of impacts as a whole system; Right - Comparison of impacts between prior and upon joining carsharing)

At scenario level, the results of the simulation are described relative to a baseline scenario, in which carsharing service is not available and potential users own private cars and have access to it. Findings suggest that carsharing can cut down the GHG emissions by 18% (Figure 4 - Left). This potential reduction is attributable to a decrease in car ownership, vehicle reuse, and fuel efficiency improvement. In the same (Figure 4 - Left), the scenario without consideration of fleet turnover leads to an overestimation of 20% reduction compared to baseline scenario.

In addition, if we limit the evaluation to GHG impacts of carsharing members in prior and upon joining carsharing organization, it has found that carsharing members collectively reduce GHG emissions by 12% (Figure 4 - Right). This reduction potential considered the impacts of fleet turnover and reuse in the GHG footprint. On the contrary, the negligence of fleet turnover has been shown to overestimate the reduction by 8% more compared to the scenario with consideration of fleet turnover, and we show therefore again that this finding is very significant.

At the vehicle level, our results confirm previous findings on the potential of carsharing vehicle in reducing GHG emissions (Martin & Shaheen, 2011; Doka & Ziegler, 2000). Most of relates to production and disposal phases (Figure 3). Some of them are, however, offset by the use phase of vehicles. Including second use, a further GHG reduction for carsharing vehicle is observed, in line with prior findings (Guyon, 2017). This confirms the hypothesis made that the exclusion of vehicle reuse will inevitably underestimate the potential contribution of carsharing.

With carsharing mobility scenario over 10 years as the analysis functional unit, the contribution of carsharing is found to be very significant and sensitive to fleet replacement. According to (Mont, 2004) and (Rodrigues, 2018), carsharing operators prefer, for various reasons, to renew their fleet each 1 or 3 years maximum. However, (Mont, 2004) assumes that the replacement strategy has a positive effect as new and efficient vehicles are introduced in the fleet. In other studies, the adverse effect related to the increase in car production and disposal is also considered but not evaluated (Chen & Kockelman, 2016; Rodrigues, 2018). In contrast, our findings reveal that vehicles replacement does not totally offset but dampens the positive effect. To our knowledge, our research is the first to evaluate all impacts of fleet turnover, thereby providing a methodological framework that do not overstate positive impacts of carsharing.

Our findings on the global impacts of electric carsharing towards the fleet replacement and second-hand market reuse sheds new light on the environmental potential of the electrification of mobility services (urban mobility, delivery services, etc.) that require replacement of their fleet. In these services, the potential contribution of electrification might not be achieved by simply adopting the EV technology. Operation strategies should also be adapted.

Finally, our research adopts a global approach that does not differentiate between local and global environmental impacts. In reality, the impacts of the electrification of carsharing are spatially distributed to the advantage of cities hosting electric carsharing programs, and to the disadvantage of countries and regions that provide and process the required materials for EV batteries. This is likely to exacerbate environmental inequalities if only the local perspective, i.e. local benefits for cities, is adopted.

CONCLUSION AND SHORTCOMINGS

Our research demonstrates the contribution of a comprehensive methodology to account for the impacts of vehicle electrification, turnover, and reuse on environmental performance of carsharing together in one place. By relying on ABM and LCA, this methodology takes into account individual travel behaviours and their wider effects on the impacts of adoption and use of carsharing in competition with other travel modes. The methodology can evaluate the environmental impacts of fleet management strategies of carsharing operators. In this respect, the proposed model addresses some of the limitations of previous studies. It provides a comprehensive insight into actual contribution of carsharing and electric carsharing.

Our research points at a trade-off between the electrification, replacement frequency and reuse of shared vehicles and their environmental impacts. To understand the overall impact, more research is needed, as there is no literature on how newer vehicles in the fleet influences carsharing adoption after fleet renewal. Understanding this trade-off, is crucial for the future of carsharing as it will help us understanding, if much larger carsharing systems are realistic and if we should really want it.

Despite our best effort to address numerous challenges faced during this research, it is still subject to several limitations. For instance, for the LCA method to be comprehensive, it needs to include all the use aspects of the product under investigation. In our case, we rely on MATSim to understand the adoption and the use of e-carsharing. Nevertheless, MATSim simulates the mobility dynamics of one day, be it weekday or weekend. In the case study of Montreal, we rely on a weekday. However, our LCA methodology has a time-frame of 10 years. To address this inconsistency, we assume that the 10 years are all made of the same weekday. This is a clear limitation to our work. In reality, the use of carsharing might differ between weekdays and weekends, or according to seasons of the year. To address this limitation, we need panel data on travel and activity behaviors. These data can produce different mobility dynamic snapshots at different times (weekday, weekend, Summer, etc.) to be fed to LCA.

Another noteworthy limitation is related to the calibration of MATSim and electric carsharing. The adoption and use of carsharing as a travel mode in competition with other modes require the calibration of MATSim. That is, the evaluation of the preferences of users towards travel modes. In Montreal, we rely on a simple calibration procedure that needs to be refined. Work in this direction is ongoing to include carsharing records in the calibration process of MATSim.

The adoption and use of old shared vehicles in the second-hand market is another limitation to this research. several research questions need to be addressed: who buys old shared vehicles? For which use? and for how long? And what would these car-buyers do in the absence of old shared cars? Answers to these questions can impact the evaluation of the environmental impacts of electric carsharing and carsharing. To overcome this limitation in future research, the proposed methodology will incorporate dynamic vehicle stock modeling. In this paper, we assumed that all old carsharing vehicles are sold to private use at the same time. This is expected not to be true, as the demand of such vehicle varies greatly from one individual to another.

Our paper relied on a literature that carsharing vehicle first useful lifespan is 3 years. With the help of dynamic vehicle stock, future paper will also be able to explore various frequencies of fleet turnover or replacement. Understanding the sensitivity of fleet replacement strategy is a key ingredient to a sustainable management and operation of carsharing.

In this paper, we do not model the relocation of shared vehicles and the impact it may have on LCA. Relocation of the fleet requires excess travel mileage to balance carsharing demand and supply. This induces an increase in the environmental and energy impacts of carsharing, especially with shared ICEVs. Future research should include relocation strategies in the transportation simulation to better assess the global impacts of the electrification of carsharing.

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