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Two-Stages Carbon Emission Pinch Analysis for Integrated System of Renewable Energy and Electric Vehicle

Ahmad F. Ramli[1,2], Ahmad M. Idris[1,2], Zarina Ab. Muis[1,2]*, Wai S. Ho[1,2], Aziatul N. Sadikin[2] and Syaza I. Ahmad[2]

[1]Process Systems Engineering Center (PROSPECT), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

[2]Department of Chemical Engineering, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

E-mail: zarinamuis@cheme.utm.my

Abstract. The introduction of electric vehicles to the transportation fleet has merged the power generation and transportation sectors into an integrated system. Rather than fuel sources, electricity is used to charge electric vehicles, so these vehicles play a vital role as an important green technology that could reduce carbon emissions in the transportation sector. This study aimed to develop a multi-stage carbon emission pinch analysis for an integrated system to optimise the energy mix for electricity generation. In the first stage, the minimum number of electric vehicles required to reduce transportation emissions was determined. In the second stage, the optimal energy mix for power generation sector was determined while including the electricity demand for the electric vehicle. Four scenarios, namely the business-as-usual scenario (S1); the public transport utilization scenario (S2); the electrification of vehicle scenario (S3); and the Integrated-Policies scenario (S4) were developed based on Peninsular Malaysia as a case study, to analyse the impact of different mitigation strategies on the country's economy. S1 was set as baseline for all the cases i.e., without any mitigation strategies. The results reveal that S4 was the best scenario, yielding a total cost saving percentage of 51.42 % compared to S1. For the power generation sector, 52 % of renewable energy (solar PV, biomass and biogas) utilisation would be needed in the energy mix to achieve the emission reduction target.

1. Introduction

The transportation and power generation sectors are responsible for almost half of the total global carbon emissions. Lately, a rising awareness of environmental issues among the youth has increased the growth of green technologies [1]. The same trend in carbon emissions can be observed in Malaysia, where transportation and power generation have had a massive impact on total carbon emission. To solve this issue, the government has set a target to achieve 45% carbon emission reduction by year 2035 [2]. One of the efforts under this vision is to introduce electric vehicles (EVs) to the transportation sector. The EV is a very promising alternative, not t only to reduce carbon emissions, but also to increase the efficiency of energy usage. However, large-scale EV usage on the road will increase energy demand on the power generation sector. In addition, the total carbon emissions for EV could then shift to power generation. This means that the full benefits of EV can

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only be reaped if clean sources of power generation such as renewable energy (RE); solar PV, biomass and biogas, were used to generate electricity. Thus, this study proposes a multi-stage energy planning technique for a system integrating power generation and transportation (electric vehicle) using a Carbon Emission Pinch Analysis (CEPA). This study focuses on the effect of the electrification of car in transportation sector. Besides, this study will provide an overview of the effect of EV implementation on the power generation sector.

Tan and Foo [3] were the first to propose CEPA, which is now the most well-known method for optimisation based on pinch principles. Numerous studies relating to carbon dioxide (CO2) emissions have been done in various countries and solutions to the emission problem have been proposed via the power generation sector [4], carbon capture and storage [5], water footprint analysis [6], chemical process [7], the transportation sector [8], and waste management [9]. The most recent application of CEPA was that of Ramli et al. [10] for the transportation sector. The study proposed different mitigation strategies for the transportation sector to achieve the target of carbon emission reduction and identified the minimum amount of energy needed for the transportation sector to implement EV. Aziz et al. [11] proposed an advance pinch analysis framework for low carbon dioxide emissions for industrial site planning. Idris et al. [12] developed a framework for an integrated water and energy system called the Water-Energy Nexus Cascade Analysis. CEPA has been widely used in studies aiming to reduce carbon emissions. A few models have been developed to identify optimal cost by implementing certain policy measures based on the economic situation. However, fewer studies have focused on an integrated system, especially the integration between transportation and power generation sectors. This study extends the work of Ramli et al. [10] and determines the minimum required RE percentage and the number of EV units needed on the road to achieve carbon emission target.

2. Methodology

In brief, EV can be considered as a zero-emission vehicle if it fully generates electricity based on RE sources such as hydro and solar. To reduce emissions from transportation, emissions from the power generation sector also need to be considered since the transportation fuel mix depend on the power generation fuel mix. Hence, this study proposes a CEPA framework for the integrated system to solve this problem.

2.1 Carbon Emission Pinch Analysis Framework for an Integrated System

The CEPA flow for the integrated system proposed in this study is shown in Figure 1. The first part of the framework shows the development of CEPA for the transportation sector. It consists of data extraction, the development of a demand and supply composite curve, and the identification of the minimum electricity generation required. The second part of the framework is the CEPA for the power generation sector, which includes data extraction, the development of a demand and supply composite curve, and the identification of the optimal energy mix for the power generation sector. The CEPA method is based on Ramli et al. [10] who first used it for the transportation sector by constructing a composite curve for demand (based on transport class) and supply (based on fuel sources) including EVs. This study proposed different mitigation strategies including fuel switching and public transport utilization for the transportation sector to determine the minimum electricity that must be generated for the transportation sector. The results obtained were then used as input for the power generation sector combined with the residential, commercial, and industrial electricity demand to form a grand demand composite curve. The CEPA method is then re-used to identify the minimum amount of fossil fuels must be shifted to RE after which the optimal energy mix for the power generation sector could be determined.

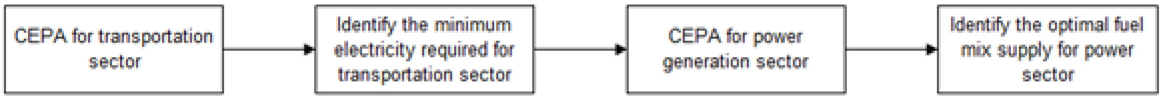

Figure 1. CEPA flow for the integrated transportation and power generation sector.

2.2 Case Study

Malaysia is a developing country that is fast becoming a developed one. Therefore, it aims to achieve a low carbon environment under the Low-Carbon Cities Framework (LCCF). Malaysia also intends to become an electric mobility marketplace [2]. This vision can be achieved by building low-carbon buildings, introducing solar township, utilising renewable energy for decentralised energy generation, using electric vehicles, providing efficient and effective mass public transport, and reducing energy and water consumption. The data needed for the CEPA framework was obtained from MAMPU [13]. The total transportation energy and the electricity demand growth rate are 2.0 % and 3.5 % respectively. The total number of vehicles on the road in Malaysia is estimated to increase up to 35 million units by 2035 based on the business-as-usual scenario, leading to an increase in the energy demand for the transportation sector by 33,783 ktoe.

In this study, different scenarios were formulated based on different mitigation strategies. S1 was established as the baseline scenario to the other proposed scenarios—this scenario assumes that the transportation demand for the year 2035 will follow the current transportation mix. Meanwhile, S2 was established to analyse the impact of increasing public transport modal share on the carbon emission reduction target. S3 was formulated to evaluate the impact of fuel switching on the fuel supply composite curve. S4 was proposed as the optimal combination of mitigation strategies in the transportation sector—by increasing public transport modal share and utilising zero or low carbon emission fuel sources (fuel switching). For economic evaluation, all scenarios were compared in term of total energy cost, total maintenance cost, and total saving cost. The total saving cost was calculated by comparing the total cost (summation of energy and maintenance cost) for each scenario to that of the baseline scenario.

3. Results and Discussion

Figure 2 shows the different composite curves developed based on the different scenario proposed. S1 is the base-case scenario (before the pinch technique is applied) while S2, S3, and S4 is the different mitigation strategies for achieving the carbon emission reduction target (after applying the pinch technique). All the proposed scenarios resulted in different total unit of vehicles, total fuel usage, and total cost savings (maintenance and fuel usage cost).

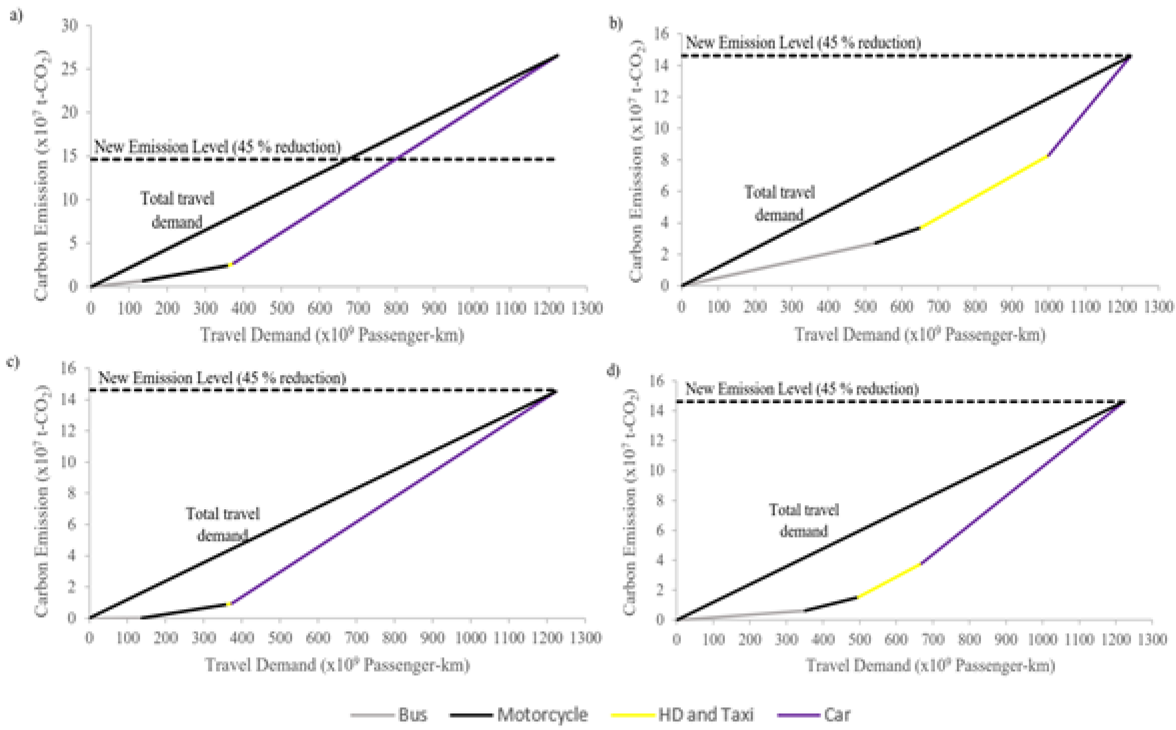

Figure 2. Various CEPA mitigation strategies for transportation sector (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, (d) Scenario 4.

Table 1 shows the summary of the results of all proposed scenarios. S1 has a higher number of vehicles on the road since it does not include any mitigation strategies compared to the other scenarios. S2 shows the lowest number of vehicles on the road with 16.08 x 109 units followed by S4 and S3 with 24.7 x 109 and 34.98 x 109 units, respectively. The S2 scenario resulted in the lowest total energy cost of RM 51.65 x 109/y since total energy consumption depends strongly on the number of vehicles on the road. However, S4 had the lowest total maintenance cost since it reduced the number of vehicles on the road and enhanced fuel switching from conventional vehicles to electric vehicle technology. EV has a simpler configuration compared to conventional vehicles, so it also has a lower maintenance cost. The total cost savings in comparison to S1 include maintenance and fuel usage. The result shows that S4 had the highest cost savings compared to S2 and S3.

Table 1. Economic evaluation for different scenarios proposed

Scenario	S1	S2	S3	S4
Total unit of vehicles ($x10^9$ unit)	34.99	16.08	34.98	24.47
Total fuel usage ($x10^3$ ktoe)	33.52	21.34	28.03	24.31
Total energy cost ($x10^9$ RM)	92.81	51.65	87.42	68.54
Total maintenance cost ($x10^9$ RM)	100.59	81.66	77.04	42.16
Total saving cost compare to S1 (%)	-	31.07	14.97	42.76
Additional electricity required ($x10^3$ ktoe)	-	0	10.37	52.30

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The main issue with EV is its higher price compared to conventional vehicle. Therefore, the government must draw up a transportation policy to balance out the EV price and make it comparable to the conventional vehicle. For example, by introducing subsidies such as tax-free incentives for EV or free charging schemes, more people would be attracted to purchase an EV. Another limitation of EV implementation in Malaysia is the charging facilities. Up until now, there are only 251 charging stations installed across Peninsular Malaysia. Of these recorded numbers, current charging stations are mostly built in urban areas such as Kuala Lumpur, Melaka, and Johor Bahru [14].

Based on the economic evaluation, S4 yielded optimal results for additional electricity demand from the transportation sector because EV hd been added to the current electricity demand. CEPA was then used once again for the power generation sector to decide on the amount of RE needed to be produced to achieve the emission target. Figure 3 shows the composite curve before the pinch technique and after the pinch technique was applied. The results reveal that 52% of electricity generation from RE would be required to achieve the emissions target. The new optimal energy mix for the power generation sector should comprise 3.68 x 106 toe of RE (52.05%), 87.05 x 106 toe of NG (33.12%), 12.09 x 106 toe of Fuel Oil (4.60%), and 26.92 x 106 toe of Coal (10.24%).

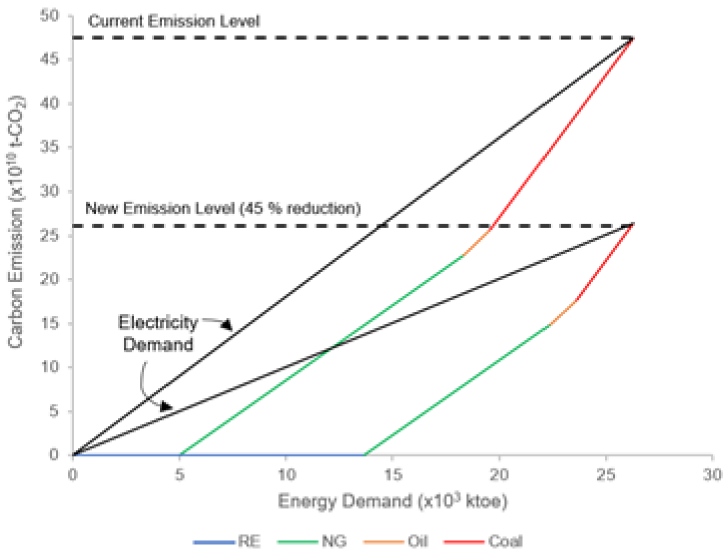

Figure 3. CEPA for power generation sector

Based on the above results, the introduction of public transport alone will not be able to fulfil the emissions target. Therefore, the focus should be on EV as an alternative option, as it clearly provides better efficiency since it has zero tailpipe emissions compared to conventional vehicles. The main issue arises from the electricity generation used to cater to EV demand. To reduce the carbon emissions by 45 %, almost half of the electricity generation must be generated from RE, as presented in Figure 3. However, it is not certain that this aim could be achieved based on the current RE availability and utilisation in Malaysia. Up until now, RE resources are mainly utilised from hydro, solar, and biomass (from palm oil residue). However, to supply this large demand for electricity, new sources of RE such as wind and tide need to be introduced into the energy mix. A recent study by Ahmad and Tahar [15] revealed that Malaysia has a huge potential for harvesting wind energy since the country has been recognised as the 29th longest coast in the world, totalling about 4,765 km. Malaysia's previous ruling government had proposed to install a nuclear power plant in Malaysia but due to poor public acceptance and recent nuclear power plant crisis, namely the Fukushima Daiichi power plant in Japan, the current government decided to terminate the project. By making changes by incorporating the above-mentioned alternatives, it is expected that Malaysia can achieve the carbon emissions target by 2035.

4. Conclusion

In summary, S4 was the best scenario, yielding a total cost saving percentage of 51.42% compared to S1, comprises of 52% power generation from renewable energy would be needed in the energy mix to achieve the emissions reduction target. The CEPA framework for an integrated transportation and power generation system was developed in this study. The method provides insight into how energy planning can be performed in both sectors simultaneously. In this study, several mitigation strategies for the transportation sector were proposed to achieve carbon reduction target. Besides, there are still numerous aspects that need to be considered by researching on reducing emissions and energy planning for the transportation sector. For instance, emission factors also depend on the driver's age, utilisation pattern, and driving style. Thus, further study is needed to explore the effect of these factors on the emissions and in different modes. In general, CEPA can still be used to develop a baseline model and as a preliminary study to solve problem related to supply and demand.

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