Conference: ESCAPE 34 – PSE 24
Paper ID: 448
Title: Priority Planning for Methane Emissions Abatement via Marginal Abatement Cost Curves (MAC) and Shapley-Shubik Power Index

Reviewer #1

Comments	Response	Details
The authors present an ingenious application of a game theory method for prioritization, Shapley-Shubik Power Indexing, in combination with the Marginal Abatement Cost (MAC) technique, to tackle suitable selection of methane emissions abatement strategies for an oil & gas sector example. I recommend this paper for publication, provided that the following minor issues are addressed:	Thank you for the generous comments. The comments have been addressed accordingly.	-
1. The authors conclude that the difference in the outcome between their study and the result obtained by the International Energy Agency (IEA) is related to a different choice in target, i.e., cost effectiveness vs. emissions reduction goal. Looking at the cited reference for the IEA Global Methane Tracker, their MAC curve considers 12 measures for emissions reduction, instead of only 5 considered in this study. Could this explain the difference between results as well? Would there be a difference in the outcomes if the same target as the IEA had been selected for the study? Please explain briefly.	Thank you for pointing this out. In this study, we focus only on the upstream segment of the Malaysian oil and gas industry. Therefore, we have excluded all downstream abatement options (4 options) reported by IEA in our study. In addition to that, IEA considered also the abatement options for onshore facilities (3 options), as they do not exist in the Malaysian oil and gas sector. This explains the rationale behind narrowing down the available options reported by IEA to only 5. We have revised the case study section for clarification as shown below. **Original:** The total emissions in Malaysian oil and gas system are estimated to be 377 kt in 2022 **Revised:** The total emissions in Malaysian oil and gas system upstream segment are estimated to be 377 kt in 2022 **Original:** This work adopts the MAC curve developed by the International Energy Agency for Malaysian oil and gas system. **Revised:**	**Section 4**

	This work adopts the MAC curve developed by the International Energy Agency for Malaysian oil and gas system. However, since the MAC curve was constructed based on the proportions of the United States, necessary adjustments must be made to align with the Malaysian context i.e., removal of onshore abatement options as the country does not possess onshore facilities.	
	Furthermore, we considered only the upstream data reported in IEA's MAC analysis for comparison. Hence, it is reasonable to conclude that narrowing our scope of study does not affect the difference found in the results. In accordance with that, we have revised the manuscript for better clarity. **Original:** On the other hand, it is worth noting that the MAC analysis by IEA prioritised pathways in this order; D, E, C, B and A. **Revised:** On the other hand, it is worth noting that the MAC analysis by IEA prioritised pathways in this order; D, E, C, B and A for the case of Malaysian oil and gas upstream segment.	**Section 5**
2. Describe in the "Methodology" section any software tools that can be applied to generate MAC curves and perform the Shapley-Shubik indexing automatically. In this contribution, the example seems fairly simple to explain the method, but it might be convenient to have an automatic tool when handling larger number of options/variables. If a simple flowsheet suffices, then state so.	Thank you for the comment. The MAC curve can be generated by developing a simple flowsheet. We have added this in the methodology section **Original:** These parameters serve as input for the MAC analysis. **Revised:** These parameters serve as input for the MAC analysis. MAC curve can be developed by formulating the algorithm in a simple flowsheet.	**Subsection 3.1**
	In the case of Shapley-Shubik index, the algorithm has to be coded and solved using a solver available in Python to determine the results automatically. We have now emphasized this in the text under Methodology **Original:**	**Subsection 3.2**

	The Shapley-Shubik power index is used to determine pivotal abatement options to achieve urgent methane emissions reduction targets. **Revised:** The Shapley-Shubik power index is used to determine pivotal abatement options to achieve urgent methane emissions reduction targets. In this work, the algorithm to determine the power index is coded using Python.	
3. Improvements for readability and publishing: a.) Perform a thorough English grammar check, including correcting any punctuation mistakes. b.) Improve the resolution of Figure 2.	a.) The manuscript has been revised accordingly b.) As suggested by the reviewer, we have improved the resolution of Figure 2.	-

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Priority Planning for Methane Emissions Abatement via Marginal Abatement Cost Curves (MAC) and Shapley-Shubik Power Index

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Abstract

Methane is the second largest emitted greenhouse gas next only to carbon dioxide. Methane is also a more potent greenhouse gas with higher global warming potential. The oil and gas sector is a major contributor to the methane emissions. Given the impact of methane emissions on global warming, there is an urgent need to report and mitigate these emissions from the sector. This necessitates the need for systematic tools to strategies the methane emissions reduction. This work proposes an integrated marginal abatement cost (MAC) and Shapley-Shubik methodology to determine the most cost-effective selection and deployment strategy of methane abatement technologies to meet the set emissions reduction targets. A case study from the Malaysian oil and gas sector is used to demonstrate the applicability of the aforementioned methodology.

Keywords: Methane emissions, Oil and gas system, Marginal abatement cost curve, Shapley-Shubik power index, Decision support tool

1. Introduction

Methane is one of the important greenhouse gases (GHGs) responsible for global warming and associated climate change effects. Methane emissions contributes about 30% to the current global warming (IEA, 2022). Notably, methane is a more potent GHG which has more than 80% higher global warming potential compared to carbon dioxide for 20-year period. Therefore, methane is viewed as a key GHG that determines the pace towards peak atmospheric temperature. This calls for concerted global effort to mitigate the methane emissions and its impact on climate change and global warming. Recognizing the above-stated challenge, the global methane pledge was signed at COP26 in 2021. The pledge mandates a 30% methane emissions reduction by signatory countries by 2030 (UNFCCC, 2021).

The major sources of methane emissions include agriculture, energy, and waste sectors. The oil and gas industry, in particular, is the largest emitter of methane emissions. It accounts for about 25% of the total global methane emissions. (IEA, 2022). There is a growing advocacy for reporting and reduction of these methane emissions from oil and gas systems. Most of these emissions are from venting, incomplete flaring, and leaks in the existing infrastructure. There are several abatement technologies available to mitigate each source of methane emissions, while each of them differs in terms of cost and its abatement capacity. This complicates the decision-making which to be selected or prioritised to ensure optimal decisions are made.

The Marginal Abatement Cost (MAC) method is a systematic cost-based approach in identifying emissions reduction technologies. MAC have been widely used in the past to illustrate the economics of climate change mitigation and have contributed to decision making in the context of climate policy (Huang et al., 2016). The concept of abatement curves has been applied since the early 1990s to illustrate the cost associated with emissions reduction (Kesicki, 2010). Additionally, MAC offers visual representation of emissions reduction and cost of abatement through a graphical plot that arranges the abatement options from the lowest to highest cost, prioritizing the most cost-effective option. Its utility has been showcased in various field, including but not limited to glass manufacturing in China (Xian et al., 2023), dairy industry in Switzerland (Huber et al., 2023), and energy sector in Russia (Keiko et al., 2022).

However, MAC method has limitations in that it does not provide insights into which of these abatement options are of utmost importance for achieving emissions reduction targets and offer a more robust long-term strategy. As such, this work employs Shapley-Shubik Power Index to determine the criticality of each abatement option in achieving methane emissions reduction targets. It was originally designed to determine the influencing power of each voter in affecting the voting outcome (Matsubara, 1989), but has now been applied to aid game-theoretic decisions for prioritization (Yahya et al., 2021). In this regard, the use of Shapley-Shubik Power Index in this work is anticipated to allow decision-makers to prioritize the deployment of abatement options that offer long-term methane emissions reduction.

2. Problem Statement

A formal problem statement can be defined as follows: The given oil and gas system consists of a set of methane emissions sources. In order to mitigate these emissions, a set of abatement technologies are considered. The proposed approach aims to determine the optimal selection and criticality of the abatement technologies in meeting the emissions reduction target. The above stated problem is solved considering the economic objective through minimizing the costs. The methodology used to solve the problem is described in Section 3.

3. Methodology

Figure 1 shows the general framework used to perform the analysis. The framework can be viewed as an integrated Marginal Abatement Cost (MAC) and Shapley-Shubik methodology. Initially, the MAC methodology, as introduced by Meier et al. (1982), is utilized to determine the most cost-effective pathway for methane emissions reduction in the given oil and gas system. Subsequently, criticality of each pathway for achieving the specified emissions reduction target is quantified using the Shapley-Shubik power index method, developed by Shapley and Shubik (1954). In this integrated analysis, the pathways determined from the mini-MAC profile are assessed based on their contribution to the overall emissions reduction, which sets the “score” for each selected abatement technology to perform the criticality assessment. The details of conducting the mini-MAC and Shapley-Shubik analysis are presented in the following subsections.

3.1. Selection of Abatement Technology using MAC analysis

The datasets pertaining to the cost and emissions profile of the source (i.e., methane emissions sources) and sinks (i.e., abatement options) are compiled. The methane emissions sources are characterized by the flow rate of methane emitted. Likewise, the abatement technologies are characterized by their emissions reduction potential, capital cost, operating cost, credits earned from methane recovery. These parameters serve as input for the MAC analysis. MAC curve can be developed by formulating the algorithm in a simple flowsheet. The output is a marginal abatement cost profile that determines the source-sink combination, which contributes to the low-cost methane emissions reduction pathway.

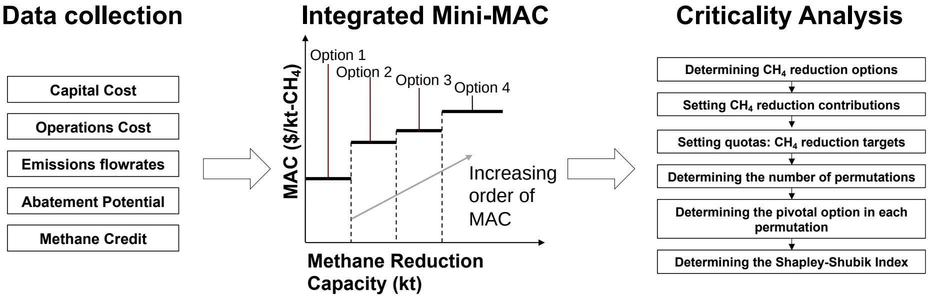

Figure 1. Overview of the proposed methodology for this present work.

3.2. Criticality of Abatement Technology using Shapley-Shubik power index

The Shapley-Shubik power index is used to determine pivotal abatement options to achieve urgent methane emissions reduction targets. In this work, the algorithm to determine the power index is coded using Python. The total number of abatement options considered is represented by $n \in N$. Their respective contributions to methane emissions reduction are represented by F_n, as shown in Eq. (1).

$$\left[q : F_{n=1}, F_{n=2}, F_{n=3}, ..., F_{n=N}\right] n \in N \tag{1}$$

In Eq. (1), a quota, q is included. The quota q, in this case, may refer to a methane emissions reduction target that the oil and gas facilities need to meet. Following this, the number of permutations is determined. The number of permutations represents the possible sequences in which these abatement options can be introduced. As mentioned earlier, the order in which these options are implemented may affect the long-term strategy for reducing methane emissions. The number of permutations can be determined using N! All permutations (or sequences of options) are then listed. For each permutation, the contribution F_n, is one-by-one added according to its sequence until its cumulative contribution reaches quota, q. The pivotal option, is the last option added to the given sequence when it reaches quota, q.

The pivotal option for other remaining permutations would differ as this depends on their order of entry into a given sequence and their contribution to meeting the quota. Hence, it is essential to determine the number of times each option is pivotal for all possible permutations. After obtaining the number of times each option is pivotal, the Shapley-Shubik power index (α_p) is calculated using Eq. (2).

$$\alpha_p = \frac{\text{Number of times an Option is Pivotal}}{N!} \tag{2}$$

4. Case Study

This section delves into a case study to demonstrate the proposed methodology outlined in Section 3. The methane emissions from the upstream segment in Malaysian oil and gas system is taken for the analysis. The sources of these emissions include venting, equipment leaks, blowdown operations, well workovers, and pneumatic devices. The total emissions in Malaysian oil and gas system upstream segment are estimated to be 377 kt in 2022 (IEA, 2022). Severable abatement options to reduce these methane emissions are available. These can be aggregated as installation of flares, installation of vapor recovery units, replacement of compressor seals and rods, replacement of pneumatics with instrument air systems, and leak detection and repair (LDAR). This work adopts the MAC curve developed by the International Energy Agency for Malaysian oil and gas system. However, since the MAC curve was constructed based on the proportions of the United States, necessary adjustments must be made to align with Malaysian context i.e., removal of onshore abatement options as the country does not have onshore facilities.Table 1 shows the summary of the revised MAC curve developed by IEA (2022).

Table 1. Abatement cost data extracted from MAC curve constructed by IEA.

Abatement option	Reduction potential (kt)	Abatement cost (USD/MBtu)	Contribution to total reduction
Install flares (A)	115	2.2	44%
Replace compressor seal or rod (B)	0.05	-16.3	0.02%
Replace with instrument air system (C)	25.80	-18	9.93%
Upstream LDAR (D)	56.20	-59.2	21.61%
Vapor recovery units (E)	63	-23.4	24.22%

5. Results

The MAC results show that the abatement technologies in the upstream segment can reduce 260 kt, which is 68.96%% of the total methane emissions in the Malaysian oil and gas system. It can be noted that installation of flares accounts for about 44% of this emissions reduction followed by installation of vapour recovery units, LDAR, and replacement with instrument air system at 24.23%, 21.61%, and 9.93% respectively. The replacement of compressor seal and rod only reduces 0.02% of the emissions reduction. In the case of cost of reduction, LDAR yields a net revenue of 59.2 USD/MBtu. Likewise, installation of vapour recovery units, installation of instrument air systems, and compressor seal replacement yields a net revenue of 23.4 USD/MBtu, 18 USD/MBtu, and 16.3 USD/MBtu, respectively; while installation of flares leads to an expense of 2.2 USD/MBtu. As shown in MAC profile, the deployment of upstream LDAR results in the highest overall cost saving, followed by the vapor recovery unit.

The Shapley-Shubik analysis is performed to determine the criticality of each abatement technologies in achieving a range of emissions reduction targets. The abatement technologies - installation of flares, the replacement of compressor seal and rod, replacement with instrument air system, LDAR, and installation of vapour recovery units are referred to as Options A, B, C, D, and E respectively. Figure 2 shows the results of the Shapley-Shubik analysis. The results show that Option D and Option E show a similar power index as the methane emissions reduction goal increases from 10% to 60%, implying that these options possess symmetrical influence regardless of the changes in the reduction goal. This can be explained as Option D and Option E exhibits very close abatement potential of 56.2 and 63 kt, respectively, and their contribution to emissions reduction is nearly interchangeable. In addition, it can be observed that Option D and Option E show the greatest influence at 10% and 60% reduction targets (37.7 kt and 226.2 kt emissions reduction, respectively), with a power index of 33.3% and an even standing with Option A. This is owing to the fact that at 10% reduction, the abatement potential for all three options can single-handedly achieve the target. However, as the reduction target increases to 20%, Option D and Option E become less pivotal and require combining effort with other abatement options to achieve the target.

Following Options D and E, the deployment of instrument air system (Option C) exhibits as the third highest cost saving. However, based on the results shown in **Error! Reference source not found.**, Option C only becomes pivotal at 20% as it can meet the target by coupling with Option D and E. At this point, Option C shows similar power index as Option D and E due to the fact that it will only meet the target by combining with either option. However, as moving to a higher target of 30% and 40%, Option C was not needed as it will not be able to meet these targets by only combining with Option A, Option D, or Option E. At 50% reduction target, Option C becomes pivotal again and shows the same power index as Option D and Option E (16.7%). This implies that the contribution between these three options to emissions reduction has become similar, where these three options will have to combine with Option A to achieve the target.

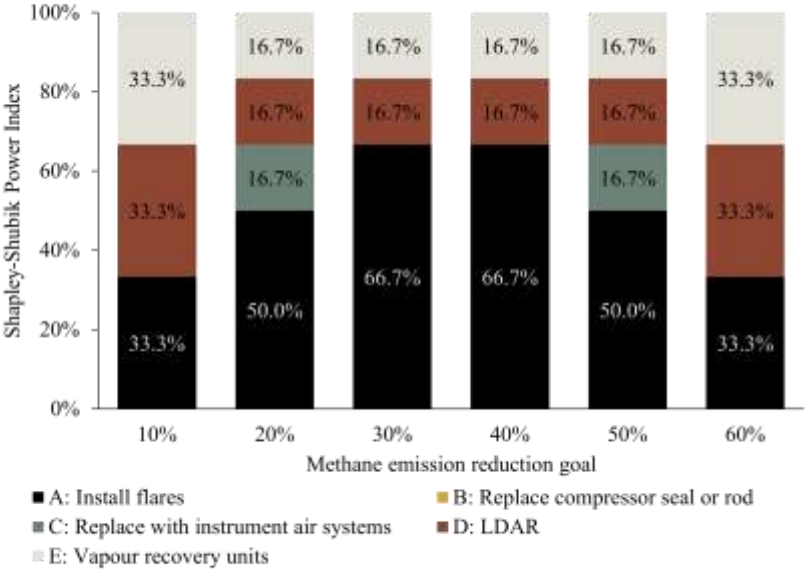

Figure 2. Shapley-Shubik Power Index for each abatement option at different methane emissions reduction target.

Moving on to the installation of flares (Option A) that constantly exhibits high power index in all reduction scenario. Option A shows the highest power index of 66.7% at 30% and 40% reduction goal, which outweighs Option D and Option E, as Option A possesses a significantly higher reduction potential (115 kt). In this case, Option D and Option E can only be pivotal when Option A is installed. However, at 50% target, Option A becomes less pivotal with power index dropped to 50%.This can be explained as at this point, combining either Option D or Option E with Option A will no longer meet the target, hence the involvement of Option C is necessary resulting in a reduction of power index for Option A. . At 60% reduction target - Option A, Option D, and Option E show an even standing, inferring that these options shared a same level of importance in the coalition and all pathways are necessary to meet the emissions reduction target. Therefore, Option C becomes insignificant and can be removed from this scenario.

The Shapley-Shubik results indicate that Option A is the most pivotal abatement technology in achieving the emissions reduction targets despite a higher abatement cost of 2.2 USD/MBtu. On the other hand, the MAC analysis by IEA prioritised pathways in this order; D, E, C, B and A for the case of Malaysian oil and gas upstream segment, which is based on cost-effectiveness. However, the integrated MAC Shapley-Shubik analysis in this work prioritise the deployment based on their significance in meeting a given emissions target, especially when become more stringent over time.

6. Conclusion

This work has presented an integrated approach that utilizes the economic dimensions of the MAC method and the systematic decision support from the Shapley-Shubik power index analysis to determine the criticality of cost-efficient abatement options for methane emissions reduction in oil and gas systems. The findings indicate that, in order to achieve the emissions reduction targets, the implementation of LDAR, which yields the highest cost saving will need to be combined with other abatement options at reduction goal of 20% or above. Conversely, the installation of flares, despite not providing cost savings and requiring additional abatement cost for implementation, emerges as the most important among the available option. The findings indicate that prioritizing abatement technologies with high emissions reduction potential, even if they are more costly, is essential to meet urgent emissions reduction targets. While strategic planning plays a crucial role in achieving these targets, incorporating economic considerations is vital to ensure the feasibility of the emissions reduction.

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