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Energy Systems CO_2 Emissions Reduction Planning in Sarawak and Qatar Using Minimum Marginal Abatement Cost Curves (Mini-MAC)

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Electricity generation using fossil fuels generates a large carbon emissions footprint. Qatar and Malaysia both have a fossil-based electricity sector. While the world is adopting stricter carbon emission targets, both countries are challenged to reduce their emissions. Options to reduce emissions include but are not limited to Carbon Capture, Utilization, and Sequestration (CCUS) and energy transition to renewable energy sources. These options vary in cost, applicability, and scale. Qatar and Malaysia are completely different in terms of economy, population, topography, natural resources, local energy demand, and emission profiles. This will require a unique strategy to reduce emissions that considers the costs, challenges, and opportunities for mitigation for each country. The current methods for strategic planning cannot account for many possible emission reduction options, cost objectives, or the individual characteristics of each emission profile and do not account for the complexity of the solutions, such as secondary emissions. To address these limitations, this work deploys an algebraic targeting technique that yields minimum marginal abatement cost (Mini-MAC) curves to represent the low-cost carbon reduction technologies available for both countries. This study focuses on the electricity sector of the state of Sarawak in Malaysia and Qatar. Due to the high cost of coal power existing in Sarawak and the availability of cheaper renewable energy, 99.84 % CO_2 could be achieved at a net profit of 13.46 USD/tCO_2. Achieving 93.5 % of CO_2 reduction from the natural gas-based grid in Qatar requires the implementation of a mix between CCUS and renewable energy at a net cost of 40 USD/tCO_2.

1. Introduction

The Paris Agreement in 2015 has made countries pursue committed efforts to limit global warming to 1.5 °C from pre-industrial levels. The signatory countries are to communicate their climate action plans, referred to as nationally determined contributions (NDCs). These plans are submitted for every five-year interval, with each successive NDCs expected to reflect more aggressive carbon reduction targets. There is also an emerging consensus to achieve net zero emissions between 2050 to 2070. These developments necessitate the need to identify potential cost-effective technologies that can be deployed for carbon reduction. Typically, sector-specific strategies are developed considering the economic activities and emission profile of a country or region.
The electricity sector is crucial for economic development, while it is also one of the largest sources of carbon emissions. The combustion of fossil-based resources for electricity generation results in significant carbon emissions, contributing 25 % of the total carbon emissions in 2021 (IEA, 2022). Multiple options are available to mitigate these emissions, which can be broadly categorized as low-carbon emission technologies, renewable energy sources, and carbon capture and storage. However, the optimal technology selection varies with countries based on their topography, natural resources, existing energy mix, and electricity demand, among others. For instance, solar-based electricity generation depends on the solar irradiance of the region. Carbon storage requires suitable geological sites, etc. Therefore, careful attention is required in the selection and deployment of the available technologies for effective decarbonization of the electricity sector.

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Qatar and Malaysia are countries with distinctive economies, energy mixes, natural resources, topography, and emission profiles. In 2021, the net electricity generation in Qatar was 48 TWh, with natural gas being the major energy resource (EIA, 2023). For the same period, Malaysian electricity generation was 166.82 TWh with coal and natural gas being the dominant fuels in the energy mix (EIA, 2021). Decarbonization of the respective electricity sectors requires unique strategies accounting for the cost, challenges, and opportunities for mitigation in each country. For example, Qatar has identified solar PV and carbon capture, utilization, and storage (CCUS) as some of the promising carbon reduction technologies, while Malaysia has hydropower, solar PV, and CCS, among others, as prospective technologies.

The minimum marginal abatement cost curve (Mini-MAC) is an effective approach that can be used to determine minimum cost carbon reduction technologies from a set of available alternatives. The mini-MAC method was first described by Lameh et al. (2021) for high-level cost analysis of carbon reduction pathways and was illustrated with pedagogical examples (Lameh et al., 2020). This was extended by accounting for the dynamic nature of renewable energy generation and energy demand in developing the mini-MAC curves (Lameh et al., 2022). This work intends to analyze carbon reduction options exclusively in the electricity sector of Qatar and Sarawak state in Malaysia. The work considers the emission and cost profile of the electricity sector in these countries while also accounting for country-specific abatement technologies in developing the mini-MAC curve. The rest of the paper is arranged as follows: Section 2 presents the methodology for developing mini-MAC curves. The emissions and cost data of the considered carbon reduction technologies in Qatar and Malaysia are described in Section 3. The mini-MAC curves are presented in Section 4 with a comparison of the curves generated for Qatar and Malaysia.

2. Methodology

The aim of this study is to compare the environmental and economic performances of CCUS and Energy Transition (ET) options in multiple regions. The methodology is based on the mini-MAC method (Lameh et al., 2021) where the considered option can be represented on CO_2 marginal abatement cost curves. The method considers the complexity of the problem by accounting for secondary emissions and capital and operating costs of the existing plants as well as the proposed options.

Given a set of existing fossil-based power sources constituting the power sector in a defined geographic region, a set of potential CO_2 utilization and storage options, and a set of potential renewable power plants, the method determines economically efficient pathways that can lead a transition toward achievable high levels of CO_2 reductions. Figure 1 shows the considered flows within the CO_2 reduction systems.

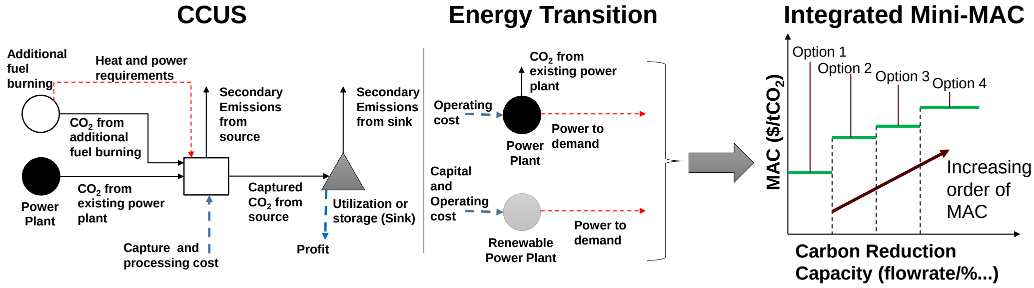

Figure 1: CO_2 reduction pathways representation and illustration on the mini-MAC curve

Each of the existing power plants is characterized by the annual power production (GWh/y), CO_2 emissions intensity (tCO_2/MWh), thermal efficiency, operating cost, which includes maintenance and fuel cost (USD/MWh), as well as CO_2 capture cost (USD/tCO_2) and secondary emissions. The CCUS and renewable energy technologies are characterized by their costs, profits, and the secondary emissions associated with their implementation. These parameters vary with the geographic location based on different factors, as discussed in Section 1. The study considers the variations that are based on the technical feasibility of the technology and the cost of fuel. Moreover, the existing systems vary based on the implemented power generation options and the fuel used to run the plants.

The parameters are estimated for the technologies considered for Sarawak and Qatar, and the values are passed to the mini-MAC algorithm described in Lameh et al. (2021), and the results for CCUS and ET options are integrated as shown in Lameh et al. (2022). This yields the different source-sink matching for the CCUS pathways and the required energy transitions (from fossil to renewables), as well as the MAC of each option and its CO_2 reduction capacity. This allows the representation and comparison of the selected options.

3. Emission and cost profiles

The following subsections summarize the emission sources, the available carbon reduction technologies and carbon sinks for Sarawak and Qatar.

3.1 Qatar

Qatar is a major producer and exporter of natural gas. The abundance of this resource makes it the primary source of energy in Qatar. The power sector runs on natural gas with 8 different plants operating at various capacities and efficiencies to produce 49.87 TWh/y (Kahramaa, 2018) and 24 MtCO_2/y. Table 1 summarizes the parameters characterizing the different power plants in Qatar. The electricity generation and efficiency are determined based on the report published by the power operator in Qatar (Kahramaa, 2018), while the total operating cost and emissions flowrate are determined assuming that the cost of natural gas extraction is 1.5 USD/GJ and emissions intensity of natural gas combustion is 50.3 kgCO_2/GJ (EIA, 2022).

Table 1: Carbon emission source - Qatar

Power plant	Electricity generation (GWh/y)	Efficiency (%)	Total operation cost (USD/MWh)	Emission flowrate (Mt CO_2/y)
RAF B	2,774	0.29	21.61	1.72
RAF B1	1,930	0.29	21.68	1.20
RAF B2	3,805	0.27	22.86	2.52
RLPC	4,190	0.33	19.70	2.33
Qpower	6,753	0.37	17.56	3.27
RGPC	11,483	0.40	16.75	5.24
Mpower	9,029	0.48	14.40	3.41
UHP	9,910	0.42	16.08	4.30

This work considers solar photovoltaics (PV) and wind as potential renewable energy options for Qatar. Due to the lack of altitudes or running rivers in Qatar, hydropower plants were disregarded. Table 2 summarizes the parameters characterizing the renewable power pathways. The capacity of solar PV was determined considering the 20 % capacity factor, while the capacity for the wind was estimated based on Méndez and Bicer (2021). The levelized cost of energy (LCOE) was estimated based on IRENA (2020) and Bellini (2020).

Table 2: Renewable energy data - Qatar

New power plant	Generation capacity (GWh/y)	Levelized cost of energy (USD/MWh)
Solar PV	9,975	15.67
Wind	2,494	53

The CO_2 capture data were determined based on Rubin et al. (2015). All the power plants had similar CO_2 capture data as the emissions stream results from burning natural gas. Natural gas combustion is considered the source of energy for the capture process, which secondary emissions level is estimated to be 0.06 tCO_2 emitted/tCO_2 captured. The capital cost is annualized over 20 years with an interest rate of 3 %. The resulting total capture cost is 38.9 USD/tCO_2 captured. The CO_2 utilization options were chosen to fit the industry portfolio of the state of Qatar by considering CO_2 utilization to produce fuels through dry reforming (Zang et al., 2021) and methanol (Perez Fortes et al., 2016), besides CO_2 utilization in EOR and storage in geological reservoirs. Table 7 summarizes the parameters characterizing CO_2 sinks.

Table 3: Carbon sinks - Qatar

Sinks	Capacity (Mt CO_2/y)	Profit (USD/t CO_2 allotted)	Fixation efficiency (t CO_2 captured/ t CO_2 allotted)
Geological Storage	10	-18	1
EOR	1	18	1
Fuels	5	-2	0.80
Chemicals	1	34	0.81

3.2 Sarawak, Malaysia

Sarawak is the largest state in Malaysia. The major electricity generation in Sarawak is from coal, natural gas, and hydropower plants. The emission flowrate and the total operating costs at these power plants are presented in Table 4, which are obtained from Sarawak Energy's Annual and Sustainability Report 2019. Electricity generation is predominantly from four coal power plants (C1, C2, C3, and C4), three natural gas power plants (NG1, NG2, and NG3), and three hydro power plants (H1, H2, and H3). The operational emissions from the hydropower plants are zero. Therefore, the hydropower plants are already carbon neutral in their generation. In comparison, coal and natural gas power plants emit carbon emissions due to fuel combustion. The total emission flowrate from these power plants is 6.39 $MtCO_2$/y.

Table 4: Carbon emission source – Sarawak (2020)

Power plant	Electricity generation (GWh/y)	Efficiency (%)	Total operation cost (USD/MWh)	Emission flowrate (Mt CO_2/y)
C1	637	30.70	74.31	0.6965
C2	553	27.30	82.89	0.6789
C3	1,563	35.60	64.44	1.4220
C4	1,515	31.90	71.71	1.5833
NG1	2,146	40.30	21.14	0.9506
NG2	625	21.20	40.36	0.5202
NG3	542	21.30	40.19	0.5425
H1	387	-	0	0
H2	15,424	-	0	0
H3	5,689	-	0	0

The carbon mitigation options for Sarawak include energy transition and CCUS. The energy transition available are renewable sources like floating solar PV plants, biomass cofiring in coal power plants, hydro power plants, and biomass power plants, as shown in Table 5. The generation capacity of the floating Solar PV and hydro power are based on the proposed plans of the Sarawak utility company. The capacity of biomass cofiring and biomass power plants are estimated based on the palm oil milling capacity in Sarawak. The levelized cost of energy (LCOE) of the renewable's are taken from ASEAN Centre for Energy (ACE, 2020).

Table 5: Renewable energy transition - Sarawak

New power plant	Generation capacity (GWh/y)	Levelized cost of energy (USD/MWh)
Floating Solar PV	4,000	51
Biomass cofiring	1,280	20
Hydropower	10,280	50
Biomass plant	2,230	92

The carbon capture data for Sarawak power plants are estimated based on Rubin et al. (2015). The secondary emissions values are 0.31 t CO_2 emitted/ t CO_2 captured for the coal power plants and 0.06 t CO_2 emitted/t CO_2 captured for the natural gas power plants. The CO_2 capture costs are estimated at 37 USD/t CO_2 captured for the coal plants and 40 USD/t CO_2 captured for the natural gas plants. The carbon utilization and storage options are presented in Table 7. The microalgae utilization in Sarawak is proposed on 2,000 ha of land. The enhanced oil recovery (MPM, 2022) and geological storage capacities (WRI, 2019) are estimated based on values obtained from online resources.

Table 7: Carbon sinks - Sarawak

Sinks	Capacity (Mt CO_2/y)	Profit (USD/t CO_2 allotted)	Fixation efficiency (t CO_2 captured/ t CO_2 allotted)
Micro algae	0.8	-81	0.85
Enhanced Oil Recovery (EOR)	2.5	-18	1
Geological storage	4	177	1

4. Marginal abatement cost curves

This section presents the results obtained for Qatar and Sarawak after generating their mini-MAC profiles.

4.1 Qatar

Figure 2 shows the MAC curve obtained for the case of Qatar. The most cost-effective options are the transitions from the power plants with lower efficiencies (RAF B, RAF B1, and RAF B2) to solar PV. The corresponding costs vary between -0.92 USD/t CO_2 and 2.68 USD/t CO_2 while achieving up to 26 % reduction from the total emissions of the power sector. Note that the negative MAC value corresponds to the cost saving from the energy transition where the cost of introducing and operating new plants (PV solar in this case) is cheaper than the cost of operating the existing plants (RAF B2). Further CO_2 reduction requires the implementation of CCUS, where CO_2 is captured from the power plants operating at higher efficiencies (Qpower, RGPC, Mpower, and UHP), and utilized in methanol production, EOR, fuel production, or stored. Wind power is activated towards the highest levels of reduction targets as the transition from RLPC to wind costs 69.86 USD/t CO_2. The MAC curve for Qatar shows that 93.5 % CO_2 reduction can be achieved for the power sector at an average cost of 40 USD/t CO_2.

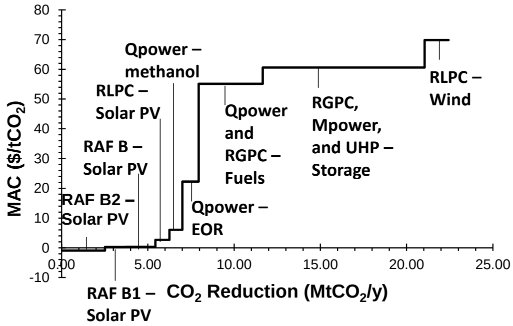

Figure 2: Mini-MAC curve for Qatar electricity sector

4.2 Sarawak

Figure 3 shows the MAC curve developed for Sarawak's electricity sector. The profile shows that the considered technologies, with their capacities, can result in total carbon mitigation of 6.38 Mt CO_2/y, a 99.84 % reduction. This can be achieved at a net cost saving resulting in an average MAC of -13.46 USD/t CO_2. Biomass cofiring at coal power plants provides the most cost-effective option for carbon reduction. In fact, biomass cofiring at C1, C2, and C3 results in cost savings of USD 49.68, USD 51.25, and USD 49.49 for every ton of carbon reduction. The total carbon reduction achieved from cofiring is 1.47 Mt CO_2/y. The transition of coal and natural gas power plants to hydropower is the next prospective mitigation option with a carbon reduction of 2.91 Mt CO_2/y and 1.06 Mt CO_2/y. The MAC for C4 and C3 transition to hydro show a saving of USD 20.77 and 15.86 USD/t of carbon mitigation. However, the MAC for NG3 and NG2 to hydro incurs a cost of USD 9.80 and USD 11.59. This might be due to higher carbon capture costs and emission flowrates at natural gas plants compared to coal plants. Finally, the EOR at NG1 with a MAC of USD 23.93/ tCO_2 results in a reduction of 0.94 MtCO_2/y.

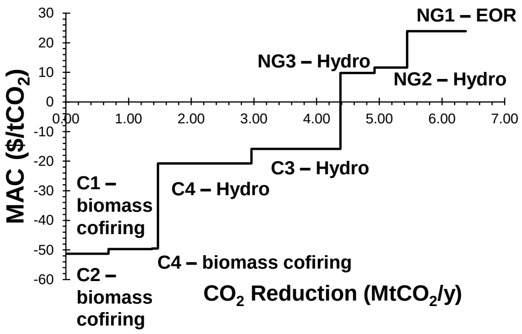

Figure 3: Mini-MAC curve for Sarawak electricity sector

Examining the individual MAC curves for Qatar and Sarawak shows that for both cases, the MAC for CCUS and ET pathways were not far apart. This indicates the necessity for a comprehensive consideration of as many possible reduction pathways as possible to yield an optimal diversified profile for CO_2 reduction. The average marginal abatement costs corresponding to the maximum achievable CO_2 reduction varied significantly between Qatar and Sarawak. While the considered options for Qatar resulted in net cost, the CO_2 reduction pathways in Sarawak yielded net savings. This is mainly due to the high operating cost of power production in Sarawak, which is a result of importing coal and operating low-efficiency natural gas power plants. Hence, the energy transition to abundant and affordable renewable energy pathways like biomass cofiring and hydropower resulted in major savings, which offset the total cost of CO_2 reduction towards profitability. This was not the case in Qatar as it is cheaper there to run the existing natural gas power plants rather than transition to renewable energy options or implement CCUS (except for RAF B2 to Solar PV transition).

5. Conclusion

This work has developed the minimum marginal abatement cost curves for the decarbonization of the electricity sector in Qatar and Sarawak state in Malaysia. The considered technologies, with their capacities, can mitigate 93.5 % and 99.84 % of the total emission flowrate in Qatar and Sarawak. The selected pathways for carbon reduction in Sarawak are biomass cofiring at coal plants, the transition of coal and natural gas plants with hydropower, and carbon capture with EOR utilization. Likewise, the optimized pathways for Qatar are transitioning from the power plants with lower efficiencies to renewable energy and implementing CCUS for the remaining emissions sources. The results indicate the need to develop country-specific strategies for decarbonization, and the mini-MAC approach can be used as an effective decision-support tool for high-level policymaking.

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