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# $CO_2$ Total Site Planning with Centralised Multiple Headers

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$CO_2$ Capture, Utilisation and Storage (CCUS) has been gearing towards the technology viable for $CO_2$ removal from the atmosphere. The successful implementation of an integrated CCUS system would open up the opportunity to develop high $CO_2$ gas field as well ensures the sustainability of gas production while minimising the impact on the environment. A methodology of $CO_2$ integration management by maximising the recovery of $CO_2$ for future utilisation and minimising $CO_2$ to be sent for sequestration through centralised $CO_2$ headers or known as $CO_2$ Total Site has been developed. It consists of one high-purity header that is attached to $CO_2$ storage or reservoir and low-purity headers that accept $CO_2$ sources at different purity to satisfy $CO_2$ demands. The multiple headers with consideration of different purity range of headers and a different number of headers are studied in this work. The application of the $CO_2$ Total Site-Problem Table Analysis (CTS-PTA) has potentially resulted in an optimal $CO_2$ target with the reduction of carbon storage of 32 % with a lower risk of $CO_2$ leakage and low $CO_2$ emission.

## 1. Introduction

The carbon emission is increasing with the continuous increase in world energy consumption. In a combination of $CO_2$ capture and storage and utilisation (CCUS), the $CO_2$ emissions can be reduced by capturing $CO_2$ and injecting it into geological storage or through utilisation. The $CO_2$ capture and storage (CCS) technology involves the capturing of $CO_2$ from the exhaust gases from large industrial facilities and appropriately storing it in geological storage sites such as depleted oil and/or gas reservoirs. However, integrated $CO_2$ capture and utilisation have been reported as a promising route toward economically viable chains of values (Stuardi et al., 2019). Pinch Analysis based methodology has been widely used in planning $CO_2$ capture and storage such as storage planning and $CO_2$ sources and sinks matches (Diamante et al., 2014). This methodology has emerged as an important branch of Process Integration (PI) for problems involving the management of $CO_2$ emissions (Tapia et al., 2018). An approach using $CO_2$ Pinch Total Site methodology was developed to manage $CO_2$ capture and $CO_2$ demands from various plants into centralised header before send to storage or sequestration (Mohd Nawi et al., 2015). The algebraic method for targeting the optimum $CO_2$ utilisation and storage based on the Pinch Analysis approach was introduced (Mohd Nawi et al., 2016). An extended methodology with consideration of different purity range of headers and a different number of headers is proposed in this paper to enhance the systematic planning and management of $CO_2$ emission for a sustainable potential alternative which can directly be related to the industrial symbiosis.

## 2. Methodology

A methodology development of the Total Site $CO_2$ Integration (TSCI) targeting technique for optimal carbon target of $CO_2$ utilisation and storage is described. Generally, the methodology comprises of four main steps which are setting the header, data extraction, constructing problem table algorithm and analysing the result.

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### 2.1 Step 1: Setting CCUS header

A potential area is selected for the implementation of TSCI planning. The area has to consist of a number of $CO_2$ sources and demands. The decision on the number of TSCI centralised headers is within the flue gas purity of $CO_2$ sources and demands. The highest flue gas purity of $CO_2$ from demand is about 99 %, so the acceptability of one of the headers must be within the range so that the demand can extract the required $CO_2$ supply from the centralised header. The rest of the centralised headers are set at lower acceptable purity range to satisfy demands which have lower purity requirement. Since this is an end-of-pipe solution, the header with high purity range is designed for reservoir storage as the final destination. For the flue gas within the centralised headers with lower acceptable purity range has to be fully consumed by the last demand at the end of its pipeline.

### 2.2 Step 2: Data extraction

The limiting data for the $CO_2$ sources and $CO_2$ demand in the selected potential area are identified and extracted based on their location along the headers from the beginning of the pipeline until the identified end. A flue gas consists of $CO_2$ gas and other various gases such as nitrogen ($N_2$), oxygen ($O_2$), carbon monoxide (CO), nitrogen oxide ($NO_x$), and sulphur oxide ($SO_x$). The extracted data includes the flue gas flow ($F_T$) and the gas $CO_2$ purity ($P_{CO2}$). The amount of $CO_2$ ($F_{CO2}$) and other gases flow rates ($F_{OG}$) can be calculated using equations adapted from Mohd Nawi et al. (2016).

### 2.3 Step 3: Problem Table Algorithm construction

An algorithmic method is developed for the planning and managing the $CO_2$ sources and demands using centralised headers. The problem table algorithm, namely $CO_2$ Total Site Problem Table Algorithm (CTS-PTA), is extended to target the maximum amount of $CO_2$ that will be utilised with the minimum amount of sequestrated $CO_2$ for multiple headers. CTS-PTA is based on the TS concept, provides the insight-based solution which can be used as a tool for CCUS planners and mechanisms to maximise the $CO_2$ utilised and minimise the $CO_2$ stored based on the location of sources and demands along the centralised header instead of their purities. By taking Header 1 (H1) as an example, the step-wise description of performing CTS-PTA is detailed in this section.
Starting from the beginning of the centralised header, the sources and demands are matched by performing $F_T$ *(Cum $F_T$)* and $F_{CO2}$ *(Cum $F_{CO2}$)* cascade, the accumulation of $F_T$ and $F_{CO2}$ cascade using equations adapted from Mohd Nawi et al. (2016). Meanwhile, the header $CO_2$ purity ($P_{H1}$) after going through each source also can be calculated using equations adapted from Mohd Nawi et al. (2016).
At demands' locations, $F_T$ and $F_{CO2}$ are accumulated from the top to the bottom row with the flow values of gases from header to specific location ($F_{T,H1-D}$, $F_{T,H1-H2}$, $F_{T,H1-H3}$, $F_{CO2,H1-D}$, $F_{CO2,H1-H2}$, *and* $F_{CO2,H1-H3}$) needs to be considered, as given in Eq(1) and Eq(2). There are two TSCI utilisation rules 1 or 2 need to satisfy for $CO_2$ demands as adapted in Mohd Nawi et al. (2016). TSCI utilisation rule 1 is for the demand requires a higher $CO_2$ purity ($P_{CO2,D,i}$) (example 99%) than that accumulation of header $CO_2$ purity ($P_{Hi,i-1}$) in the header (example 86%). A mixture of pure $CO_2$ from the $CO_2$ generator is required to satisfy the requirement of high purity demands. TSCI utilisation rule 2 is for the demand requires equal or lower $CO_2$ purity ($P_{CO2,D,i}$) than the accumulated $CO_2$ purity in the header. Any $F_T$ from the header can directly be supplied to the demand by assuming that the demand can accept equal or higher purity sources.
The minimum target of $F_T$ and $F_{CO2}$ that is to be sent to the dedicated geological storage can refer to the last row of Column 7 (*Cum $F_T$*) and Column 8 (*Cum $F_{CO2}$*) respectively. The total fresh $CO_2$ required from the centralised pure $CO_2$ generator is the summation of Column 12 ($F_{CO2,FC}$). For the subsequent headers, the same procedures are applied except the fresh $CO_2$ supply from the centralised $CO_2$ generator. The cleaner flue gas from the header with higher acceptable purity range has the potential to be utilised instead of using pure $CO_2$ to satisfy higher $CO_2$ purity demands for TSCI utilisation rule 1. The amount of $F_T$ taken from H2 ($F_{T,H2-D}$) and H1 ($F_{T,H1-D}$) to satisfy demand at H2 can be calculated using Eq(3) and Eq(4).

$$Cum\ F_{T,H2,i} = Cum\ F_{T,H2,i-1} + F_{T,H2-D,i} + F_{T,H2-H3,i} \quad (1)$$
$$Cum\ F_{CO2,H2,i} = Cum\ F_{CO2,H2,i-1} + F_{CO2,H2-D,i} + F_{CO2,H2-H3,i} \quad (2)$$
$$F_{T,H2-D,i} = (F_{T,D,i} \cdot P_{H1,i-1} - F_{T,D,i} \cdot P_{D,i}) / (P_{H1,i-1} - P_{H2,i-1}) \quad (3)$$
$$F_{T,H1-D,i} = F_{T,D,i} - F_{T,H2-D,i} \quad (4)$$

For the situation where $CO_2$ in the header with a lower purity range is a deficit to supply to a demand in the header. Instead of using fresh, pure $CO_2$, the surplus of $CO_2$ from another header with higher purity range can direct referring the amount of needed $CO_2$ with neglecting the purity demand in the header since it tends to be ideally below than the other headers. For example, in header 3 (H3), the surplus of $CO_2$ from H1 can supply to H3 to solve the deficit problem in H3 to satisfy the requirement of demand in H3. Eq(5) and Eq(6) described the gases transportation between other headers to H3, listed in Column 29 and Column 31 (Table 2c).

$$F_{T,H1-H3,i} = Cum\ F_{T,H3,i-1} + F_{T,D,i} \quad (5)$$
$$F_{T,H2-H3,i} = Cum\ F_{T,H3,i-1} + F_{T,D,i} - F_{T,H1-H3,i} \quad (6)$$

As only H1 is designed to be sent to geological storage, the last row of *Cum* $F_{T,H2}$ (Column 16) and *Cum* $F_{T,H3}$ (Column 24) should not give any access where the surplus value of $F_T$ should be reduced by part of the sources, preferably the source with lower purity. When the last row of *Cum* $F_T$ gives a zero value, that is the Pinch Point of the TSCI system.

## 3. Results and discussion

The CTS-PTA method was demonstrated with a combined case study data from Texas by Hasan et al. (2014) and another case study from an industrial site by Munir et al. (2012). The arrangement of the sources and demands across the headers is assumed as shown in Table 1. As the mentioned sign of flow rate, the positive values indicate $CO_2$ input flow rate into the header whereas the negative values are output flow rate from the header. A CTS-PTA is performed to optimise the carbon target of CCUS with a few scenarios. The effect of different acceptable purity range and number of headers are analysed through the application of CTS-PTA on five different scenarios.

*Table 1: Arrangement of $CO_2$ sources and demands across the header*

| S/D | Description | $P_{CO2}$ (%) | $F_T$(t/h) | $F_{CO2}$(t/h) | $F_{OG}$(t/h) |
|---|---|---|---|---|---|
| S1 | Cement | 90 | 138.8 | 124.9 | 13.9 |
| S2 | Refineries/Chemical | 70 | 608.5 | 425.9 | 182.5 |
| S3 | Power (coal based) | 85 | 1,174.3 | 998.2 | 176.1 |
| D1 | Beverage plant | 99 | -50.0 | -49.5 | -0.5 |
| S4 | Power (NG based) | 88 | 101.5 | 89.3 | 12.2 |
| S5 | Agricultural | 65 | 69.9 | 45.4 | 24.4 |
| D2 | Enhance oil recovery | 80 | -208.3 | -166.6 | -41.7 |
| S6 | Petrochemical | 80 | 615.4 | 492.3 | 123.1 |
| S7 | Gas processing | 90 | 36.5 | 32.8 | 3.6 |
| S8 | Iron & Steel (corex) | 95 | 27.9 | 26.5 | 1.4 |
| D3 | Methanol Production | 50 | -83.3 | -41.7 | -41.7 |
| D4 | Micro Algae Production | 10 | -220.0 | -22.0 | -198.0 |

### 3.1 Example scenario 1

In this scenario, TSCI is studied by using one header approach. All the $CO_2$ sources and demands are integrated into one header. The minimum amount of remaining $CO_2$ in Column 8 after cascading is 1,821.2 t/h which is needed to be sent to geological reservoirs for $CO_2$ storage. There is 47.4 t/h amount of fresh $CO_2$ from the $CO_2$ generator is needed to blend with the header gas in order to reach the requirement of the demand. The $CO_2$ purity in the stream header at the end is accumulated to 81 % which is still under the acceptable range as the assumption of only 80 % and above purity can enter geological storage.

### 3.2 Example scenario 2,3,4

In this scenario, TSCI is studied by using two header approaches. Each of the headers is set to a certain purity range. Each of the headers is set to a certain purity range. For Scenario 2, H1 is set to 80 - 99.99 % while H2 is set to 50 - 79.99 %. For Scenario 3, H1 is set to 90 - 99.99 % while H2 is set to 50 - 89.99 %. For Scenario 4, H1 is set to 85 - 99.99 % while H2 is set to 50 - 84.99 %. However, H2 for all scenarios (2,3,4) does not have access to storage. For this reason, any of an excess $CO_2$ in the last row (Cum $F_{Ti,H2}$) needs to be deducted with the sources from H2. This is the Pinch Point of the system where the $CO_2$ from the H2 which cannot be stored, might still be emitted to the environment. After performing the CTS-PTA, the minimum of amount of remaining of $CO_2$ in Column 8 (H1) after cascading is 1,582.6 t/h, 179.8 t/h, and 917.2 t/h for Scenario 2, 3, and 4.

### 3.3 Example scenario 5

For further scenario, three headers were set with a purity range between 90 – 99.99 % for H1, 70 – 89.99 % for H2 and 50 – 69.99 % for H3. The results are shown in Table 2a, 2b and 2c.

*Table 2a: CTS-PTA Scenario 5 for H1*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | S/D | Header | $P_{CO2,S/D}$ (%) | $F_T{}^{H1}{}_{,S/D}$ (t/h) | $F_{CO2}{}^{H1}{}_{,S/D}$ (t/h) | $F_{OG}{}^{H1}{}_{,S/D}$ (t/h) | Cum $F_{T,H1}$ (t/h) | Cum $F_{CO2,H1}$ (t/h) | $P_{CO2,H1}$ | $F_{CO2,H1-D}$ (t/h) | $F_{T,H1-D}$ (t/h) | $F_{CO2,FC-D}$ (t/h) |
| 1 | S1 | H1 | 90.0 | 138.8 | 124.9 | 13.9 | 138.8 | 124.9 | 0.90 | | | |
| 2 | S2 | H2 | 70.0 | | | | 138.8 | 124.9 | 0.90 | | | |
| 3 | S3 | H2 | 85.0 | | | | 138.8 | 124.9 | 0.90 | | | |
| 4 | D1 | H1 | 99.0 | -50.0 | -49.5 | -0.5 | 133.8 | 120.4 | 0.90 | -4.5 | -5.0 | 45.0 |
| 5 | S4 | H2 | 88.0 | | | | 133.8 | 120.4 | 0.90 | | | |
| 6 | S5 | H3 | 65.0 | | | | 133.8 | 120.4 | 0.90 | | | |
| 7 | D2 | H2 | 80.0 | | | | 133.8 | 120.4 | 0.90 | | | |
| 8 | S6 | H2 | 80.0 | | | | 133.8 | 120.4 | 0.90 | | | |
| 9 | S7 | H1 | 90.0 | 36.5 | 32.9 | 3.7 | 170.3 | 153.3 | 0.90 | | | |
| 10 | S8 | H1 | 95.0 | 27.9 | 26.5 | 1.4 | 198.2 | 179.8 | 0.91 | | | |
| 11 | D3 | H3 | 50.0 | | | | 184.8 | 167.6 | 0.91 | | | |
| 12 | D4 | H3 | 10.0 | | | | 0.0 | 0.0 | 0.00 | | | |

*Table 2b: CTS-PTA Scenario 5 for H2*

| | 1 | 2 | 3 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| i | S/D | Header | $P_{CO2,S/D}$ (%) | $F_T{}^{H2}{}_{,S/D}$ (t/h) | $F_{CO2}{}^{H2}{}_{,S/D}$ (t/h) | $F_{OG}{}^{H2}{}_{,S/D}$ (t/h) | Cum $F_{T,H2}$ (t/h) | Cum $F_{CO2,H2}$ (t/h) | $P_{CO2,H2}$ | $F_{CO2,H2-D}$ (t/h) | $F_{T,H2-D}$ (t/h) |
| 1 | S1 | H1 | 90.0 | | | | | | | | |
| 2 | S2 | H2 | 70.0 | 608.5 | 426.0 | 182.6 | 608.5 | 426.0 | 0.70 | | |
| 3 | S3 | H2 | 85.0 | 1,174.3 | 998.2 | 176.1 | 1,782.8 | 1,424.1 | 0.80 | | |
| 4 | D1 | H1 | 99.0 | | | | 1,782.8 | 1,424.1 | 0.80 | | |
| 5 | S4 | H2 | 88.0 | 101.5 | 89.3 | 12.2 | 1,884.3 | 1,513.4 | 0.80 | | |
| 6 | S5 | H3 | 65.0 | | | | 1,884.3 | 1,513.4 | 0.80 | | |
| 7 | D2 | H2 | 80.0 | -208.3 | -166.6 | -41.7 | 1,676.0 | 1,346.1 | 0.80 | -167.3 | -208.3 |
| 8 | S6 | H2 | 80.0 | 615.4 | 492.3 | 123.1 | 2,291.4 | 1,838.4 | 0.80 | | |
| 9 | S7 | H1 | 90.0 | | | | 2,291.4 | 1,838.4 | 0.80 | | |
| 10 | S8 | H1 | 95.0 | | | | 2,291.4 | 1,838.4 | 0.80 | | |
| 11 | D3 | H3 | 50.0 | | | | 2,291.4 | 1,838.4 | 0.80 | | |
| 12 | D4 | H3 | 10.0 | | | | 2,256.2 | 1,810.2 | 0.80 | | |

*Table 2c: CTS-PTA Scenario 5 for H3*

| 1 | | 3 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | S/D | $P_{CO2,S/D}$ (%) | $F_T^{H3}{}_{,S/D}$ (t/h) | $F_{CO2}^{H3}{}_{,S/D}$ (t/h) | $F_{OG}^{H3}{}_{,S/D}$ (t/h) | Cum $F_{T,H3}$ (t/h) | Cum $F_{CO2,H3}$ (t/h) | $P_{CO2,H3}$ | $F_{CO2,H3-D}$ (t/h) | $F_{T,H3-D}$ (t/h) | $F_{T,H1-H3}$ (t/h) | $F_{CO2,H1-H3}$ (t/h) | $F_{T,H2-H3}$ (t/h) | $F_{CO2,H2-H3}$ (t/h) |
| 1 | S1 | 90.0 | | | | | | | | | | | | |
| 2 | S2 | 70.0 | | | | | | | | | | | | |
| 3 | S3 | 85.0 | | | | | | | | | | | | |
| 4 | D1 | 99.0 | | | | | | | | | | | | |
| 5 | S4 | 88.0 | | | | | | | | | | | | |
| 6 | S5 | 65.0 | 69.9 | 45.4 | 24.5 | | | | | | | | | |
| | | | | | | 69.9 | 45.4 | 0.65 | | | | | | |
| 7 | D2 | 80.0 | | | | | | | | | | | | |
| | | | | | | 69.9 | 45.4 | 0.65 | | | | | | |
| 8 | S6 | 80.0 | | | | | | | | | | | | |
| | | | | | | 69.9 | 45.4 | 0.65 | | | | | | |
| 9 | S7 | 90.0 | | | | | | | | | | | | |
| | | | | | | 69.9 | 45.4 | 0.65 | | | | | | |
| 10 | S8 | 95.0 | | | | | | | | | | | | |
| | | | | | | 69.9 | 45.4 | 0.65 | | | | | | |
| 11 | D3 | 50.0 | -83.3 | -41.7 | -41.7 | | | | -54.1 | -83.3 | -13.4 | -12.2 | | |
| | | | | | | 0.0 | 0.0 | | | | | | | |
| 12 | D4 | 10.0 | -220.0 | -22.0 | -198.0 | | | | | -220.0 | -184.8 | -167.6 | -35.2 | -28.2 |
| | | | | | | 220.0 | 195.9 | 0.89 | | | | | | |
| | | | | | | 0.0 | | | | | | | | |

In Scenario 5, there is no excess amount of $CO_2$ in H1 after cascading, a zero value at the last row of Cum $F_{CO2}$ (Column 8 in Table 2a). This is due to the deficit in $CO_2$ supply at H3. There is about 13.4 t/h of flue gas supplied to H3 at the location of D3 in order to cover the $CO_2$ supply deficit to satisfy the demand. Besides, an amount of 184.8 t/h flue gas from H1 and an amount of 35.2 t/h flue gas from H2 are supplied into H3 to fulfil the requirement of demand 4. Refer to Table 2a, it can be seen there is excess flue gas in H2, there is about 2,256.2 t/h Cum $F_{T,H2}$ at the last row of Column 16. The same procedure is carried out to deduct the amount of $CO_2$ supply from the sources that supply into H2, which are S2, S3 and S8. All the amount of sources are eliminated from supplying to H2 except for the S3. The supply amount of flue gas from S3 is changed to 142 t/h from 1,174.3 t/h. There is no excess accumulation of $CO_2$ at the end of H2. As mentioned previously, there is about 35.2 t/h of flue gas is needed to inject into H3 to satisfy the D4 which is one of the demands that extract flue gas from the header. However, there is also a large amount of captured $CO_2$ might still emit into the environment which up to 1,795.8 t/h.

The result obtained from all the scenarios is analysed and compared as shown in Table 3. Table 3 includes the base case study as the reference to the CCS without CCUS concept applied. The adjustment of purity range and number on the headers gave impact in the amount and purity of $CO_2$ which is sent to geological storage. The amount of fresh $CO_2$ and the carbon emission are also affected by the mentioned factors. With the consideration of TSCI, Scenario 3 and 5 are giving a negative result as there is a large potential $CO_2$ emission as the captured carbon from the sources might still be emitted into the environment although they have high percentage reduction of carbon storage with a low amount of $CO_2$ sent to geological storage.

The amount of $CO_2$ sent to geological storage in Scenario 2 and 4 are lower than in Scenario 1. However, there is an amount of captured $CO_2$ from sources that cannot be stored and might still be emitted to the atmosphere as the Pinch Point of H2 is achieved. In Scenario 1, there is no Pinch Point should be considered and no captured $CO_2$ released into the atmosphere and all the excess CO is sent to storage. The result of purity in sequestered $CO_2$ for Scenario 1 is barely lower than 80 % which prove that one header approach would create uncertain storage condition and lead to difficulty in controlling the $CO_2$ purity from various emission sources. In short, Scenario 1 might still be a questionable selection of CCUS planning depending on the condition of sources and demands. For Scenario 2 and 4, the lower flow rate required in fresh $CO_2$ results in a reduction of overall

capital cost when compared to the base case without utilisation consideration. Scenario 2 gives a lower carbon emission, but higher in the amount of $CO_2$ sent to geological storage.
In contrast, Scenario 4 gives a better result in minimising the amount of $CO_2$ sequestered but higher amount of $CO_2$ emission. The carbon emissions storage life capacity is estimated for both Scenarios; there is a potential of extending storage life about 10.3 % and 34.6 % for Scenario 2 and 4. As the objective of this study is the optimal carbon target of CCUS, Scenario 2 has higher potential in the low carbon emission planning with the optimal CCUS condition compared to Scenario 4.

*Table 3: Summary of results between CCS (base case) and all the scenarios (1,2,3,4,5)*

| | Base Case: CCS (without utilisation header) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|---|
| $CO_2$ sequestered in storage (t/h) | 1,764 (sources with ≥ 80 % purity) | 1,821.2 | 1,582.5 | 179.8 | 1,153.1 | 0 |
| Purity of $CO_2$ sequestered | 84 % | 81 % | 84 % | 91 % | 86 % | - |
| Fresh/outsource of $CO_2$ needed (t/h) | 279.8 | 47.4 | 46.5 | 45.0 | 46.5 | 45.0 |

## 4. Conclusions

An extended methodology of TSCI has been developed by the numerical technique which is known as CTS-PTA to analyse the impact of purification range and number of headers. This newly developed method has contributed significantly to addressing the maximum utilisation of $CO_2$ and minimum $CO_2$ to be stored in geological storage. With all the scenarios given, the most optimal $CO_2$ target can reduce a 32 % of $CO_2$ storage with a lower risk of $CO_2$ leakage and low potential of $CO_2$ emitted into the environment. The technique is now available for CCUS planners to design their future headers according to CCUS mechanisms for significant $CO_2$ reduction planning and management.


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