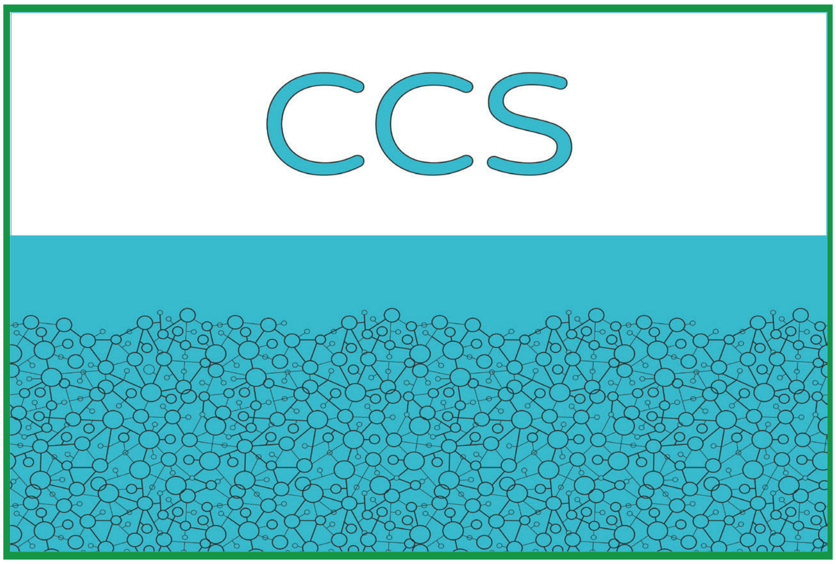
Samuel Neaman Institute
for National Policy Research

Environment & Energy

Long-term Planning
Industry & Innovation
Physical Infrastructure
Health
Human Capital
Higher Education
Society
Education
Economy
Science & Technology

A Comparative Study of the Carbon Capture Alternatives in the Production of Natural Gas-based Transportation Fuels

Prof. Ofira Ayalon
Dr. Miriam Lev-On
Dr. Daniel Madar
Dr. Perry Lev-On
Naama Shapira



September
2018

מוסד שמואל נאמן
למחקר מדיניות לאומית

בחינה השוואתית של חלופות לתפיסת פחמן בתהליכי ייצור דלקים מבוססי גז טבעי

A Comparative Study of the Carbon Capture Alternatives in the Production of Natural Gas-based Transportation Fuels

פרופ' אופירה אילון – מוסד שמואל נאמן
ד"ר מרים לב און – מוסד שמואל נאמן
ד"ר דניאל מדר – SP Interface
ד"ר פרי לב און – מוסד שמואל נאמן
נעמה שפירא – מוסד שמואל נאמן

מוגש למדענית הראשית - המשרד להגנת הסביבה
מחקר מספר 163-1-5

30.09.2018

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY (Hebrew)

רקע

תפיסת ואחסון פחמן (CCS - Carbon Capture and Storage) הינו תהליך בו פחמן דו-חמצני (פד"ח) נתפס מפליטות של תהליכים תעשייתיים ותהליכי הפקת חשמל, ומאוחסן ללא יכולת להיפלט לאטמוספירה. מטרת התהליך לצמצם את האפקט של פליטת גזי חממה אנתרופוגניים (ממקור אנושי) על שינוי האקלים.

אין מדובר בטכנולוגיה אחת, אלא בחבילה שלמה של טכנולוגיות ותהליכים. חלק מהם פועלים בהצלחה כבר עשרות שנים, בעוד אחרים נמצאים תחת פיתוח או בשלבי מעבר לשימוש בקנה מידה תעשייתי.

באופן בסיסי, CCS מורכב משלושה שלבים עיקריים:

- **תפיסה** - הפרדת פד"ח מגזים אחרים בתהליך התעשייתי או בתהליך הפקת חשמל. לאחר מכן הוא נדחס לקראת שינוע;
- **שינוע** - העברת הפד"ח, בד"כ באמצעות צינורות, מאתר תפיסתו אל אתר אחסנה; ו-
- **אחסון** - הזרקת פד"ח אל תצורות קרקע או לאקוויפרים תת-קרקעיים לשם כליאה ארוכת טווח.

לחילופין, ניתן לשלבו בתהליכים תעשייתיים ליצירת מוצרים (CCU - Carbon Capture and Utilization), או להזריק אותו לשדות נפט וגז מתדלדלים לשם שיפור קצב ההפקה של האחרונים (EOR - Enhanced Oil Recovery).

ההתעניינות בעולם בטכנולוגיות CCS גוברת בשל שלושה גורמים עיקריים:

1. הבנה כללית גוברת כי לשם צמצום השפעות שינוי האקלים יש צורך בצמצום בפליטות גזי חממה, שהמשמעותי בהם הוא פד"ח.
2. ההבנה כי לא ניתן להשיג בקלות או במהירות צמצום משמעותי בפליטות פד"ח על ידי שימוש בפחות אנרגיה או על ידי מעבר לדלקים דלים בפליטות פחמן. 85% מהאנרגיה בשימוש האדם מקורה בדלקי מאובנים, ולשנות זאת לוקח זמן רב. CCS יכול לעזור בצמצום מסיבי של פליטות עד אשר ניתן יהיה להשלים מעבר לאנרגיות דלות בפליטות פחמן.
3. מודלים כלכליים של שימוש באנרגיה מראים כי הוספת CCS לרשימת הכלים לצמצום פליטות גזי חממה, מוזילים בצורה משמעותית את העלות של צמצום שינוי האקלים. מחקרים אחרים חישבו כי החל מ-2030 CCS יהיה חלק חשוב מכלים בעלי עלות-תועלת גבוהה לצמצום פליטות גזי חממה.

כיום, CCS הינו כלכלי רק בחלק מצומצם של מקרים, כאשר מרבית העלות מקורה בתהליך תפיסת הפד"ח. חסמים נוספים הם קושי בשימוש בפד"ח כחומר גלם, חוסר וודאות רגולטורי, אי קבלה ציבורית, קושי באיתור ואפיון אתרי אחסון, אי הכרה בעלויות החיצוניות של פליטת גזי חממה, ונושאי חבות (liability, מי נושא באחריות במקרים של נזק). לאור זאת, יש הגורסים כי CCS לעולם לא יתרום בצורה משמעותית לצמצום פליטות גזי חממה.

אולם, בדוח ה-IPCC (Intergovernmental Panel on Climate Change) האחרון (2014) חושב, כי **ללא ההטמעה של טכנולוגיות CCS, המחיר להשגת ריכוז פד"ח אטמוספרי של עד 450 חל"מ (חלקיקים למיליון - Parts Per Million), יהיה יקר יותר ב-138%**, לעומת תרחישים שכוללים CCS.
על פי רוב המודלים לניבוי מצב האקלים במאה ה-21, הגבלת ריכוזי פד"ח אטמוספרי מתחת ל-450 חל"מ, תהיה אפשרית רק על ידי צמצום פליטות גזי חממה בעזרת CCS בהיקף של 10-15%. רק מיעוט מהמודלים שמשיגים תוצאות דומות, אינם לוקחים בחשבון יישום CCS.

ענף התחבורה אחראי לכ-15% מפליטות **כל גזי החממה** האנתרופוגניים בעולם, ובישראל לכ-26% מפליטות הפד"ח שמקורן **בשריפת דלקים**.
מטרת התוכנית הלאומית לתחליפי דלקים ולתחבורה חכמה הינה לצמצם את התלות הלאומית בנפט מיובא, ולהניע את רכבי ישראל בדלקים מבוססי גז טבעי ישראלי, מבוססי חשמל ומקורות אנרגיה מתחדשים.
למרות העובדה כי שריפת יחידת אנרגיה של גז טבעי פולטת פחות פד"ח לעומת שריפת יחידת אנרגיה של נפט, עיבוד הגז הטבעי לדלקים נוזליים מוסיף פליטות גזי חממה למחזור החיים של הדלקים הללו וגורם לכך שהפער בפליטת פד"ח בין שריפת גז טבעי ונפט יכול להצטמצם בכ-40%. במקרה של דלק GTL (Gas-to-Liquid) למשל, שימוש בו בתחבורה גורם לפליטת יותר גזי חממה לעומת דלקים מבוססי נפט כאשר בוחנים את מחזורי החיים מהבאר לגלגל של הדלקים. יתרה מכך, עשרות מחקרים מאז תחילת העשור מראים כי חיפוש, הפקה, שינוע, חלוקה ושימוש בגז טבעי כרוך בפליטה של כמויות גדולות של גז החממה הפוטנטי מתאן, ברמות אשר עלולות לבטל את היתרון של הגז הטבעי בפליטת פד"ח בעת שריפתו לעומת נפט ופחם. לכן, יש חשיבות לבדיקת דרכים לצמצום פליטות גזי החממה ממערך תחליפי הדלקים לתחבורה מבוססי הגז הטבעי.
בעולם פועלים נכון ל-2018, 18 פרויקטים בקנה מידה גדול (עם כושר תפיסה שנתי של מעל 400 אלף טון פד"ח) ועוד כעשרים בשלבי פיתוח שונים, בנוסף פועלים (או בבנייה) כ-15 מפעלים קטנים יותר (עם כושר תפיסה שנתי של 50-400 אלף טון פד"ח). המפעלים הקיימים הם בעלי יכולת תפיסה מצרפית של יותר מ-30 מיליון טון בשנה, והם מיושמים בתעשיות שונות:

תחנות כוח שפועלות על פחם או גז:

- SaskPower's Boundary Dam קנדה, אמור לתפוס 90% מפליטות הפד"ח של היחידה עליה מותקן.
- Kemper County מיסיסיפי ארה"ב, אמור לתפוס 65% מפליטות הפד"ח.
- Petra Nova טקסס, אמור לצמצם את פליטות הפד"ח מהיחידה עליה מותקן ב-33%.

תעשיות לייצור פלדה, מלט, כימיקלים, הפקת מימן, דשנים וזיקוק:

- Shell Quest קנדה – מפחית פליטות מתהליך עיבוד חולות נפט.
- Emirates Steel Industries אבו דאבי – מפעל לייצור ברזל ופלדה.

- Lake Charles Methanol ארה"ב – מפעל לייצור מתנול מתזקיקי נפט אשר נמצא בשלבי פיתוח אחרונים ואמור לתפוס 77% מהפד"ח המיוצר.

מפעלים לעיבוד גז טבעי:

- Val Verde טקסס פועל מ-1972.
- Sleipner הים הצפוני, נורבגיה - פועל מ-1996, נחשב הפרויקט הראשון שמיישם מיטיגציה, כאשר יישום אחסון הפד"ח הינו תולדה של מס פחמן שהטילה הממשלה הנורבגית.
- Petrobras Lula Oil Field ברזיל - פועל במים אולטרה עמוקים החל מ-2013, נחשב לפרויקט שמאחסן בעומק הרב ביותר.
- Gorgon Project אוסטרליה - פרויקט שעוסק בהנזלת גז טבעי ופועל מ-2016, יישום CCS אמור להפחית את פליטות גזי החממה של הפרויקט ב-40%.
- Jilin CCS facility סין - המפעל האחרון שהצטרף לרשימת הפרויקטים באוגוסט 2018.

פתרונות ה-CCS, אשר נבחנו לשילוב במערך תחליפי הדלקים לתחבורה מבוססי גז טבעי, בשלים טכנולוגית עם לפחות שימוש בקנה מידה תעשייתי אחד. לרובם מעל עשר שנות ניסיון בעולם.

מטרות המחקר

ביצוע סקירה של תחום ה- CCS בעולם: טכנולוגיות, מתקנים, יישום ומדיניות.

בחינה השוואתית של טכנולוגיות CCS שונות מבחינת בשלות, יעילות ועלות.

בחינה השוואתית ראשונית של יישום פתרונות CCS במערך תחליפי הדלקים לתחבורה מבוססי גז טבעי אשר עשויים לקום בישראל.

הצעה ראשונית לכלי מדיניות לקידום הנושא.

ממצאים עיקריים

לממצאים של מחקר זה השלכות ליישום אפשרי של CCS בישראל:

עיבוד גז טבעי: הגז הטבעי הגולמי אשר נמצא עד כה בישראל עני מאוד בפד"ח. לכן, אין צורך ב-CCS במהלך עיבוד הגז הטבעי הגולמי.

ייצור CNG (Compressed Natural Gas - גז טבעי דחוס): CCS לא רלוונטי לייצור CNG, כיוון שלא נפלט פד"ח בתהליך.

ייצור מתנול: אם יוקם מתקן לייצור מתנול מגז טבעי בישראל, שילוב CCS במפעל כזה יכול להפחית פליטות גזי חממה ב-11% ממחזור החיים של יצויר ושימוש במתנול. זאת במידה ויעשה שימוש חוזר בפד"ח הנתפס במהלך ייצור המתנול (CCU), ומה שלא ינוצל - יאוחסן. בנוסף לכך, התהליך מגדיל את ייצור המתנול ב-20%, מביא לצמצום דרישות האנרגיה של התהליך ב-5% ומצמצם את צריכת הגז הטבעי ב-16%.

באמצעות תמריצים ל-CCS במפעל לייצור מתנול, שינוע ואחסון הפד"ח שנתפס יכולים להתבצע ללא עלות נטו. בישראל, בהתאם לתחזית של מנהלת תחליפי דלקים, אם היקף השימוש במתנול לתחבורה ב-2030 יגיע לכ-10%, צפוי כי ניתן יהיה לתפוס, לשנע ולאחסן 0.25-0.35 מיליון טון פד"ח בשנה בעלות של 10-35 מיליון ₪ (ערכי אמצע שנת 2016). יתכן וניתן יהיה לבצע זאת אפילו ללא תוספת עלות נטו כלל, מכיוון שרוב תהליך תפיסת הפד"ח, והתשתיות הנדרשות לכך, כבר קיימים במפעל מתנול, עם או בלי יישום CCS\CCU, ומכיוון שתהליך ה-CCU מגביר תפוקה ומצמצם תשומות.

היות ורוב תהליך תפיסת הפד"ח מתבצע בכל מקרה במפעל לייצור מתנול גם ללא CCS, השפעות סביבתיות של תוספת CCS\CCU למפעל כזה הן זניחות. יתרה מכך, מכיוון ש-CCU במפעל מתנול מביא לחסכון אנרגטי ולחסכון בצריכת גז טבעי, צפוי כי יישום CCS\CCU במפעל מתנול ישפר את טביעת הרגל האקולוגית של מפעל לייצור מתנול.

ייצור GTL: אם יוקם מתקן לייצור GTL בישראל, הממצאים מראים כי שילוב של CCS יוכל לצמצם 37% מפליטות גזי החממה ממחזור החיים של ייצור ושימוש ב-GTL. יישום טכנולוגיות CCS, כולל שינוע ואחסון, יכול להתבצע בעלות נצוכה יחסית, מכיוון, שבדומה למפעל מתנול, רוב תהליך תפיסת הפד"ח, והתשתיות הנדרשות לכך, כבר קיימים במפעל GTL, עם או בלי יישום CCS\CCU. עלות תפיסת טון פד"ח במפעל GTL נמוך פי עשר מתפיסתו בתחנת כוח מונעת בגז טבעי - NGCC (Natural Gas Combined Cycle).

עפ"י צפי השימוש ב-GTL לתחבורה ב-2030, צפוי כי ניתן לתפוס, לשנע ולאחסן 1.63-3.38 מיליון טון פד"ח בשנה בעלות של 115-426 מיליון ₪ (ערכי אמצע שנת 2016). ערך זה משקף התייקרות בייצור הדלק ב-3.5% בלבד.

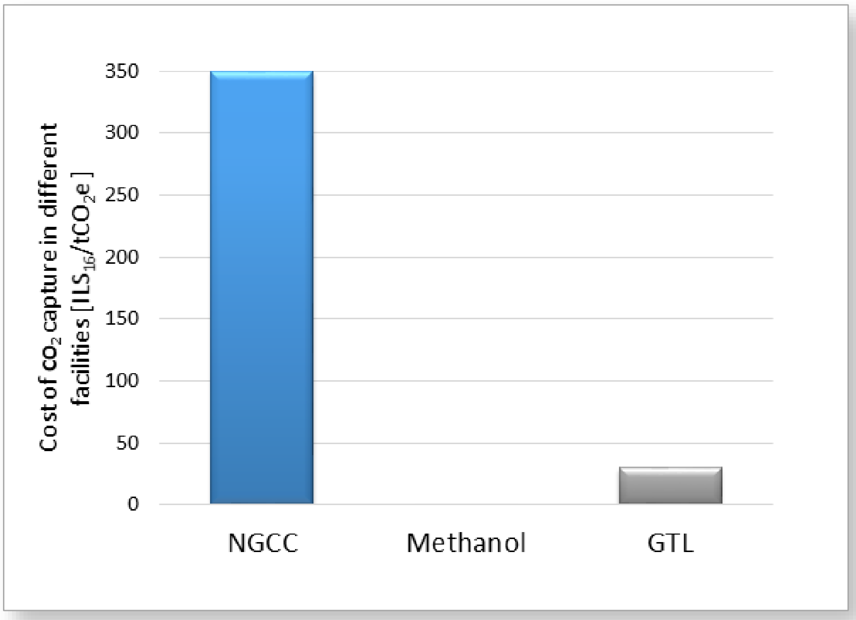
היות ורוב תהליך תפיסת הפד"ח מתבצע בכל מקרה במפעל לייצור GTL גם ללא CCS, השפעות סביבתיות של תוספת CCS\CCU למפעל כזה הן זניחות.

ייצור חשמל בתחנת כוח מונעת בגז טבעי (NGCC): חשמל מהווה תחליף לדלק קונבנציונאלי, כאשר הוא משמש להנעת רכבות, רכבים חשמליים או רכבים היברידיים נטענים. עבור תחנת כוח NGCC, הממצאים מראים כי שילוב CCS יוכל לצמצם 65% מפליטות גזי החממה ממחזור החיים של ייצור ושימוש בתחבורה חשמלית. עם זאת, העלות היא הגבוהה ביותר לכל טון פד"ח, מכיוון שצריך להקים תשתית מלאה לתפיסת הפד"ח.

במידה ומיישמים CCS **בכל** תחנות הכוח המונעות בגז בישראל ב-2030, ניתן לתפוס, לשנע ולאחסן 23-27 מיליון טון פד"ח בשנה בעלות שנתית של 7,456-18,693 מיליון ₪ (ערכי אמצע שנת 2016). ערך זה משקף התייקרות בייצור החשמל בהיקף של 30-60%. לשם יישום CCS בתחנת כוח, יש צורך בהקמת תשתית ייעודית מלאה, וספיגת ירידה של 15-25% בכושר ייצור החשמל (מה שמצריך שריפת יותר דלקים כדי להגיע לייצור אותה כמות חשמל). לפיכך, ליישום CCS בתחנות כוח השפעות ניכרות על הסביבה, בעיקר בתחומים של רעילות לאדם, פגיעה במקורות מים מתוקים, פגיעה במקורות מים מלוחים, רעילות לחיים יבשתיים ובמידה פחותה יותר, אך עדיין משמעותית, בעודף חומרי הזנה במקורות מים והעלאת חומציות.

החישוב מראה כי אם תופסים פד"ח בתחנות NGCC, לפי החלק היחסי הצפוי לתחבורה חשמלית בישראל מסך כל צריכת החשמל הצפויה בישראל ב-2030, ניתן לתפוס, לשנע ולאחסן 1-1.8 מיליון טון פד"ח בשנה בעלות שנתית של 320-1,206 מיליון ₪ (ערכי אמצע שנת 2016).

איור א' מראה את סך העלויות בש"ח של תפיסת טון פד"ח בישראל במתקנים לייצור תחליפי דלקים מבוססי גז טבעי (העלות אינה כוללת שינוע ואחסון פד"ח, אשר זהה לכל המתקנים).



איור א': עלות תפיסת פד"ח במתקנים לייצור תחליפי דלקים מבוססי גז טבעי

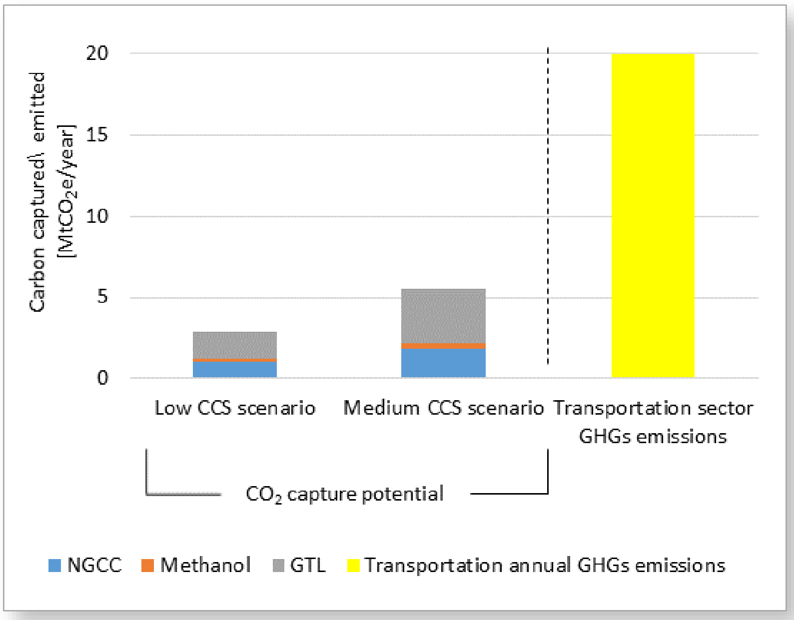
שקלול CCS מכל במתקני תחליפי דלקים מבוססי גז טבעי בישראל:

יישום צנוע של CCS במתקני תחליפי דלקים מבוססי גז טבעי (0.25 מיליון טון פד"ח לשנה ממתנול, 1.63 מיליון טון פד"ח לשנה מ-GTL, ומיליון טון פד"ח לשנה מתחנות כוח NGCC), יביא לתפיסה, שינוע ואחסון של 2.9 מיליון טון פד"ח בשנה, בעלות של 445-923 מיליון ₪ (ערכי אמצע שנת 2016).

היקף זה מהווה צמצום של כ-15-20% בפליטות גזי החממה מתחבורה בישראל ב-2030 (לפי תחזית חדירת תחליפי דלקים לתחבורה ב-2030 ללא CCS). זהו היקף סביר אם מסתכלים רק על ענף התחבורה, אך היקף זה, בסופו של דבר, מתורגם לצמצום של פחות מ-3% מפליטות גזי החממה בישראל ב-2030.

יישום בינוני של CCS במתקני תחליפי דלקים מבוססי גז טבעי (0.35 מיליון טון פד"ח לשנה ממתנול, 3.38 מיליון טון פד"ח לשנה מ-GTL, 1.8 מיליון טון פד"ח לשנה מתחנות כוח NGCC), יביא לתפיסה, שינוע ואחסון של 5.5 מיליון טון פד"ח בשנה, בעלות של 755-1670 מיליון ₪ (ערכי אמצע שנת 2016). היקף זה מהווה צמצום של כ-27-37% בפליטות גזי החממה מתחבורה בישראל (לפי תחזית חדירת תחליפי דלקים לתחבורה ב-2030 ללא CCS). זהו היקף מכובד אם מסתכלים רק על ענף התחבורה, אך, בסופו של דבר, היקף זה מתורגם לצמצום של פחות מ-6% מפליטות גזי החממה בישראל ב-2030.

איור ב' מציג את התוצאות שיושגו בהפחתת שווה ערך של טון פד"ח לשנה אל מול פליטות גזי החממה מענף התחבורה בישראל. שתי העמודות השמאליות מייצגות את הפוטנציאל לתפיסת פד"ח בשתי חלופות שונות: יישום צנוע של CCS; יישום בינוני של CCS.



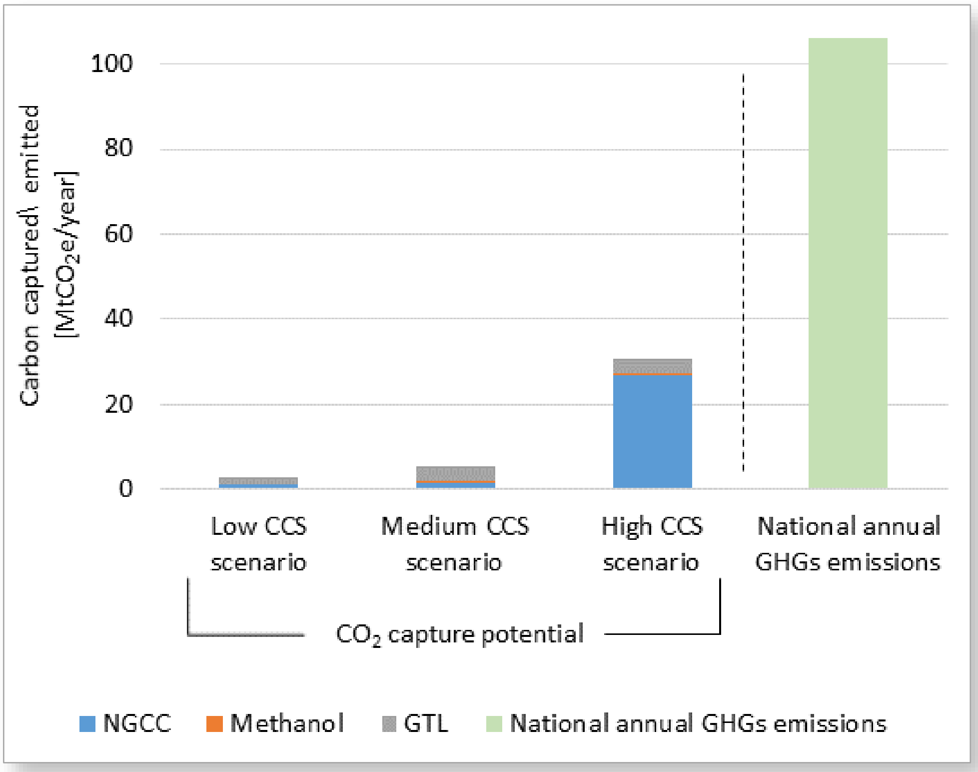
איור ב': פוטנציאל מצטבר לתפיסת פד"ח במתקני תחליפי דלקים מבוססי גז טבעי בישראל ב-2030, אל מול פליטות גזי החממה מענף התחבורה בישראל

כחול - פוטנציאל לתפיסת פד"ח בתחנות כוח מונעות גז טבעי (NGCC); כתום - פוטנציאל לתפיסת פד"ח במפעל לייצור מתנול; אפור - פוטנציאל לתפיסת פד"ח במפעל לייצור GTL; צהוב - צפי פליטות גזי חממה בישראל מענף התחבורה ב-2030 (תרחיש עסקים כרגיל).
התוצאות המלאות מוצגות בטבלה 5-1 בדו"ח המלא.

חלופות אלו לא מספיקות כדי לצמצם באופן משמעותי את פליטות גזי החממה **הלאומיות** של ישראל.

יישום נרחב של CCS במתקני תחליפי דלקים מבוססי גז טבעי, ובעיקר יישום מסיבי של CCS בתחנות כוח מונעות גז טבעי (0.35 מיליון טון פד"ח לשנה ממתנול, 3.38 מיליון טון פד"ח לשנה מ-GTL, 27 מיליון טון פד"ח לשנה מתחנות כוח NGCC), יביא לתפיסה, שינוע ואחסון של 24.9-30.7 מיליון טון פד"ח בשנה, בעלות של 7,581-19,157 מיליון ₪ (ערכי אמצע שנת 2016). היקף זה מהווה 25-30% מפליטות גזי החממה **הלאומיות** של ישראל ב-2030. רק יישום חלופה זו, או יישום חלקי שלה (למשל, יישום CCS בחצי מתחנות הכוח המונעות בגז טבעי בישראל), יכולים לצמצם באופן משמעותי את פליטות גזי החממה של ישראל, בהתאם לתפקיד שדו"ח ה-IPCC רואה ל-CCS.

איור ג' מציג את התוצאות שיושגו בהפחתת שווה ערך של טון פד"ח לשנה אל מול פליטות גזי החממה הלאומיות של ישראל. שלוש העמודות השמאליות מייצגות את הפוטנציאל לתפיסת פד"ח בשלוש חלופות שונות: יישום צנוע של CCS; יישום בינוני של CCS; יישום נרחב של CCS.



איור ג': פוטנציאל מצטבר לתפיסת פד"ח במתקני תחליפי דלקים מבוססי גז טבעי בישראל ב-2030, אל מול פליטות גזי החממה הלאומיות

כחול - פוטנציאל לתפיסת פד"ח בתחנות כוח מונעות גז טבעי (NGCC); כתום - פוטנציאל לתפיסת CO_2 במפעל לייצור מתנול; אפור - פוטנציאל לתפיסת פד"ח במפעל לייצור GTL; ירוק - צפי פליטות גזי חממה בישראל ב-2030 (תרחיש עסקים כרגיל).

התוצאות המלאות מוצגות בטבלה 5-1 בדו"ח המלא.

אחסון פד"ח בישראל:

שבעה אקוויפרים מלוחים עמוקים (Deep saline aquifers) בדרום ישראל מסוגלים לקלוט את כל כמויות הפד"ח השנתיות שנזכרו לעיל במשך 130-800 שנים. זהו פרק זמן מספק עד למעבר מלא מאנרגיה מבוססת פחמן. מכל הפד"ח שיוזרק לקרקע, חושב כי רק 0.15% ידלוף במשך 230 שנה. מאגרים אלו הם די והותר לצרכי מדינת ישראל, ומהווים את האפשרות המתאימה ביותר לאחסון פד"ח כרגע.

ממצאים עיקריים מסקירת המדיניות לקידום CCS

הממצאים בדבר נוכחות פרויקטים של CCS בקנה מידה גדול במדינות כמו ארה"ב, קנדה, אוסטרליה וסין מצביעים כי יישום CCS בקנה מידה גדול מצריך:

1. תלות בינונית-גבוהה בייצור/צריכה של דלקי מאובנים, ושאיפה אמיתית של הממשל לצמצום פליטות גזי חממה ממקורות אלו; יש להבהיר כי הגדרת תלות זו היא יחסית וכוללת סדרה של קריטריונים המבוססים על חלקן של המדינות בייצור וצריכה של דלקים פוסיליים מתוך כלל הייצור והצריכה העולמיים. יישום טכנולוגיות תפיסה ואחסון לא בא במקום קידום אנרגיות מתחדשות אלא כאלמנט משלים. על פי הסוכנות הבינלאומית לאנרגיה, יישום אנרגיות מתחדשות והתייעלות אנרגטית לא

יספיק לצורך השגת יעדי הסכם פריז ומכאן מחייב שילוב אמצעים אחרים. טכנולוגיות תפיסה ואחסון נחשבות לאמצעי זול יותר מאלטרנטיבות אחרות. ראו גם פרק 1.2 ואיור 1-1 בדו"ח המלא.

2. מדיניות לאומית ואזורית תומכת לגיבוי שאיפה זו, כולל מנגנונים פיננסיים ישירים (להקמת מתקנים) או עקיפים (מיסוי פחמן - Carbon pricing);

מס פחמן נחשב אלמנט תומך ליישום טכנולוגיות תפיסה והפחתה. הפרויקט בים הצפוני בנורבגיה (Sleipner) הפועל כבר למעלה מעשרים שנה, הינו תולדה של מס פחמן שהטילה הממשלה הנורבגית. כדאיות כלכלית דורשת מחיר פחמן של למעלה מ-60 דולר לטון לשנה.

עם זאת, ההצדקה להקמת מתקנים תלויה באלמנטים רבים (מאפייני התהליך התעשייתי, תכולת הפד"ח, מציאת שימושים רווחיים ועוד) ולא ניתן לקבוע אותה על סמך גובהו של מס פחמן בלבד.

סביר כי מס פחמן לבד לא יהווה תמריץ מספק ליישום טכנולוגיות תפיסה בקנה מידה נרחב וידרשו אמצעי מדיניות נוספים, כגון הטלת חובה ליישום בהיתר הפעלה למתקנים, בדומה לפרויקט האוסטרלי (The Gorgon gas project).

3. מסגרות חוקיות ורגולטוריות להבטחה כי כל הרכיבים בשרשרת הטכנולוגית של CCS מטופלים;

4. קיום רשימה בדוקה של אתרי אגירה לפד"ח, תוך הערכה/בדיקה ופיתוח מוקדם של אתרי אגירה.

בנוסף, ראוי לציין כי מדינות בעלות מוכנות רגולטורית גבוהה ליישום CCS פיתחו את תעשיית ה-CCS שלהם במשך שני עשורים לפחות. תהליך זה כלל פיתוח התחייבויות מדיניות, פיתוח חקיקה, אפיון אגירה, רתימת התעשייה ומחקר יישומי.

לכן, **אתגרים ייחודיים ליישום CCS כוללים**:

- ודאות במסגרת המדיניות (הכרחי),
- צורך במיקוד בתחומי תעשייה רבים,
- שילוב מסחרי לרוחב כל שלושת החלקים של שרשרת ה-CCS (תפיסה, שינוע ואחסון),
- איתור ואפיון מוקדמים של אתרי אחסון גיאולוגיים מתאימים,
- מסגרות חקיקה ורגולציה אשר מספקות התחייבויות ברורות והוראות חבות,
- יציבות במאמצי מחקר ופיתוח,
- מודעות קהילתית גוברת בחשיבות CCS.

לשם יישום CCS בהיקף הנחוץ להפחתה של מצאי פליטות גזי חממה לאומיים, יש צורך במאמצים ליידע את הציבור על חשיבות הנושא. הציבור צריך להבין מהו בדיוק CCS, כיצד הוא עובד, ומה השיקולים בעד ונגד. מודעות ציבורית רחבה ליעילות CCS תעזור להרגיע חששות, לקדם דעות חיוביות ולעודד את מעורבות הקהילות היכן שפרויקטים של CCS מתוכננים לקום.

המלצות מדיניות

סקירת המדיניות אשר בוצעה בעבודה זו מחזקת את התפיסה כי שלבים בתהליך גיבוש מדיניות הינם קריטיים בהתנעת ו/או האצת פיתוח CCS. אלו כוללים:

- וידוא ומעקב ממשלתי של היצמדות למטרות הפחתת פליטות לכל רוחב המשק, באופן עקבי עם מטרות הסכם פריז (2015) לצמצום פליטות גזי חממה.
- גיבוש מדיניות, לרבות שימוש בתמריצם כלכליים (המעודדים התייעלות אנרגטית, הקמת מתקני אנרגיה מתחדשת והקמת מתקני CCS או שימוש במס פחמן) להשגת צמצום פליטות בטווח בינוני בענפים רבים במשק, בהתאמה למטרות הפחתת הפליטות לטווח ארוך.
- לכלול באופן מפורש CCS בתוכניות לאומיות להתמודדות עם שינוי אקלים או בהצהרות מדיניות מרכזיות בתחום, ולהדגיש כיצד CCS יכול לשחק תפקיד לצד טכנולוגיות דלות בפחמן אחרות.
- הבטחת ודאות במדיניות ע"י התחייבות ממשלתית מתמשכת.
- ייזום מעורבות ציבורית/פרטית על מנת לתת מענה לסיכון בין חלקי התפיסה, השינוע והאחסון בשרשרת ה-CCS, לשם צמצום סיכון כללי.
- הקדשת תשומת לב מיוחדת להאצת השקעה באיתור ואפיון אתרי אחסון, לאור העובדה כי נדרש זמן רב לפיתוח אתרים אלו.

מגבלות המחקר

עבודה זו מהווה סקירה מוגבלת של תחום ה-CCS. סקרנו את התחום והצגנו תוצאות ראשוניות ליישום CCS בישראל. לא ביצענו סקירה טכנו-כלכלית ליישום CCS בישראל וכן, לא ביצענו ניתוח סביבתי מלא ליישום CCS בישראל.

העבודה לא בחנה ולא ממליצה על הקמת מתקנים לייצור מתנול או GTL וההערכות שהוצגו הן **במידה** ומתקנים כאלה יוקמו בישראל.

בישראל תנאים ייחודיים בתחום דלקי המאובנים לעומת מדינות אחרות, לדוגמא, מקודמות תוכניות להקמת מפעלים לייצור מתנול ו-GTL שישמשו כתחליפי דלקים לתחבורה. אלו לא מתקנים נפוצים ולכן הם נחקרים פחות, לעומת CCS מתחנות כוח, למשל. לכן, דרושים מחקרים נוספים שיבחנו פתרונות אלו, בדגש על יישומם בישראל.

המלצות עבור פעילות המשרד להגנ"ס ולהטמעת תוצאות המחקר בישראל

למפעלי ייצור מתנול ו-GTL צפויות להיות השפעות ניכרות על הסביבה, כאשר רוב תשתיות תפיסת הפד"ח הן חלק מתשתיות מפעלים אלה, עם או בלי יישום CCS. לכן, ***אם*** יבנו מפעלי מתנול ו-GTL, כחלק מהתוכנית הלאומית לתחליפי דלקים לתחבורה, מומלץ להתנות בניה זו ביישום CCS\CCU במתקנים אלו. כך, יתכן וניתן להשיג צמצום של עד 25% בפליטות גזי החממה ממערך התחבורה (כתלות בהיקף החדירה של דלקים אלו למערך התחבורה בישראל). יתרה מכך, מומלץ לפתח תשתיות שינוע ואחסון עבור הפד"ח הנתפס. ללא

ודאות בשינוע ובאחסון פד"ח, כפי שצוין לעיל, תפיסת פד"ח בלבד, ללא אחסונו, הינה מיותרת. כל זאת יתכן וללא עלות נטו במפעל מתנול, ותוך עליה קטנה מאוד בהוצאות במפעל GTL.

עקב העלות הכלכלית הגבוהה וההשפעה הסביבתית המשמעותית של יישום CCS בתחנות כוח מונעות גז טבעי, מומלץ לקדם בדיקת כדאיות ליישום פתרון זה אל מול חלופות אפשריות אחרות (אנרגיות מתחדשות, גרעין, התייעלות אנרגטית וכו').

המלצות למחקר המשך

מכיוון שזוהי סקירה מוגבלת ומכיוון שבישראל מאפיינים ייחודיים ל-CCS, לא ניתן היה ללמוד תחום זה לעומק, בעיקר, יישומו בישראל. אנו ממליצים על מחקר נוסף בתחום:

- ניתוח טכנו-כלכלי ליישום CCS בישראל.
- הערכת השפעות על הסביבה של יישום CCS בישראל, בעיקר בתחנות כוח.
- מחקר ספציפי ביישום CCS\CCU במפעלי מתנול.
- מחקר ספציפי ביישום CCS במפעלי GTL.
- השוואה בין פתרונות אנרגיה דלים בפחמן: CCS, אנרגיות מתחדשות, אגירת אנרגיה ואנרגיה גרעינית.
- מחקר על פתרונות CCU חדשניים אשר יכולים לתרום להורדת מחיר תפיסת פד"ח, בדומה לפתרון שקיים במפעל מתנול.
- מחקרים נוספים בתחום אחסון פד"ח באקוויפרים מלוחים עמוקים בישראל.

EXECUTIVE SUMMARY (English)

The Israeli Fuel Choices and Smart Mobility Initiative (FCI) has targeted natural gas as a leading source for a variety of new transportation fuels to reduce dependence on petroleum-based fuels. Although an increase in natural gas use, at the expense of petroleum, will help in reducing ambient air pollution from transportation - it will not reduce Israel's greenhouse gases (GHGs) emissions. Israel is a signatory to the United Nations Framework Convention on Climate Change and has signed the Paris climate accord where it has committed to reduce its GHGs emissions on a per capita basis.

One of the options to be evaluated as part of the introduction of natural gas-based transportation fuels is the potential deployment of Carbon Capture and Storage (CCS) technologies to remove carbon dioxide (CO_2) emissions from industrial processes, and either store or use it to prevent its release to the atmosphere. CCS refers to a suite of technologies that are used to capture CO_2 from industrial processes and electricity generation. Some of these technologies have been operated successfully for decades, while others are under development or in transition to large-scale applications.

Basically, CCS consists of three main stages: (a) **capture** for the separation of CO_2 from other gases produced from facilities, (b) **transport** for conveying the pressurized CO_2, usually via pipelines, and (c) **storage (or sequestration)** for injection of CO_2 into deep underground rock formations or aquifers.

This study focused on a literature review of emerging CCS technologies and their level of maturity. It also entailed an analysis of the compatibility of deploying such technologies to different natural gas-based transportation fuels in Israel, which include: Compressed Natural Gas (CNG), methanol (for gasoline blends), and Gas-to-Liquid (GTL) fuel products. This one year comparative study was not intended to be a complete feasibility study and the results presented intend to *provide an indication* of the range of costs and potential emissions reduction and are not a conclusive cost-effectiveness analysis of options. The study also summarizes challenges for CCS deployment and policy options.

The data compiled in this study has implications for potential implementation in Israel:

- ***If* CCS is deployed at a methanol plant** it could reduce CO_2 emissions by 11% and boost methanol production by 20% while lowering process energy demand by 5%, and natural gas consumption by 16%. All this might be achieved at no net increased cost. However, this captured CO_2 amount is less than 0.5% of Israel's 2030 annual GHGs emissions.

- ***If*** **CCS is deployed at a GTL plant** it can potentially reduce 37% of CO_2e emissions from the GTL life-cycle at a relatively low cost since most of the CO_2 capture process is already an integral part of the GTL conversion process. However, the captured CO_2 amount is less than 2-4% of Israel's 2030 annual GHGs emissions.
- **Natural gas power plants**[1] **with CCS** can capture 65% of their life-cycle GHGs emissions. This can represent up to 30% of Israel's 2030 annual GHGs emissions. Among the scenarios analyzed here, this solution is the only one that can really reduce the national GHGs emissions. However, it is also by far the most expensive one.
- **Israel's deep saline aquifers** can receive the captured CO_2 from methanol plants, GTL plants and natural gas power plants for 130-800 years (depending of the amount captured).

Lessons learned from existing large scale projects in the US, Canada, Australia and China are making clear that large scale CCS deployment would require a genuine desire by the government to address growing emissions from fossil energy sources; supportive national policies to back the overall goal; legal and regulatory frameworks to ensure all components of the CCS technology chain are addressed; and a portfolio of storage sites that have been identified. It is clear, that there are unique challenges for CCS deployment that require predictability in policy setting, the need for multi-industry focus with commercial integration across all three elements of the CCS chain including addressing liabilities and risks associated with each stage. Therefore, it would be imperative to conduct robust research & development on the topic and increase community awareness of the importance of CCS and the role it plays in mitigating GHGs emissions and climate change.

The conclusions from the survey conducted in this study highlight the policy-making process elements that are critical to enable and/or accelerate the deployment of CCS, including:

    - Government tracking and verification of adherence to the economy-wide emissions reduction targets, consistent with the aims of the Paris Agreement.

---

[1] Power will be used in electric vehicles and, therefore, meet the goal of reducing the dependency on fuel.

- Designing policy, including economic incentives (to promote energy efficiency, renewable energy and incentivizing construction of CCS plants. Negative incentives can include carbon tax on GHG emissions, which may achieve medium-term emissions reduction in a range of sectors and in line with these longer-term targets. It is reasonable to assume that carbon tax alone will not be a sufficient incentive to implement large-scale carbon capture and storage technologies and will require additional policy measures, such as imposing a mandatory operating permit conditions on facilities, (i.e, Australian project, The Gorgon Gas Project).
- Explicitly including CCS in national climate action plans or similar flagship policy statements, which either implicitly or explicitly acknowledge how CCS can play a role alongside other low carbon technologies.
- Securing policy certainty via a government commitment that has been demonstrated to extend beyond political cycles and to be resilient to conflicting political demands.

Key Policy Findings

The findings from large-scale projects in countries such as the US, Canada, Australia and China indicate that large-scale CCS deployment requires:

1. A moderate to high dependence on fossil fuel production/consumption and a genuine desire by the government to address growing emissions from these sources;
2. Supportive national and regional policies to back this overall desire, including direct or indirect financing mechanisms, including economic incentives to promote energy efficiency, renewable energy and incentives for the construction of CCS plants. Negative incentives can include carbon tax;
3. Legal and regulatory frameworks to ensure all components of the CCS technology chain are addressed; and
4. A portfolio of storage sites which have been identified, with early opportunities appraised and developed.

In addition, it can be noted that nations with high regulatory readiness for CCS deployment have developed their CCS industry over at least two decades. This has included the development of policy commitments, legislative development, and storage characterization, as well as industry engagement and applied research.

Therefore, unique challenges for CCS deployment include:

- Predictability in policy setting is paramount,
- Need for multi-industry focus,
- Commercial integration across all three elements of the CCS chain,
- Early identification and characterization of suitable geological storage sites,
- Legal and regulatory regimes that provide clear obligations and liability provisions,
- Robustness in R&D efforts,
- Increasing community awareness of the importance of CCS.

As discussed further in Section 4.3, for CCS to be implemented on the scale necessary to affect GHG emissions, efforts are needed to inform and raise awareness among the general public about CCS. The public needs to know exactly what is CCS, how it works and what are its pros and cons. Broad public awareness of CCS' effectiveness will help alleviate concerns, promote positive opinions and encourage the engagement of the communities where CCS projects are planned to be undertaken.

Policy Recommendations

The survey conducted here reinforces elements of the policy-making process that are critical to enabling and/or accelerating the deployment of CCS. These include:

- Government tracking and verification of adhering to the economy-wide emissions reduction targets, consistent with the aims of the Paris Agreement.
- Designing policy to achieve medium-term emissions reduction in a range of sectors and in line with these longer-term targets.
- Explicitly including CCS in national climate action plans or similar flagship policy statements, which either implicitly or explicitly acknowledge how CCS can play a role alongside other low carbon technologies.
- Securing policy certainty via a government commitment that has been demonstrated to extend beyond political cycles and to be resilient to conflicting political demands.
- Establishing public/private engagement to address the risk between the capture, transport and storage elements of the CCS chain, thus reducing overall risks.
- Devoting special attention to accelerating investment in storage exploration and characterization, in view of the long lead times for development of such locations.

- Including economic incentives to promote energy efficiency, renewable energy and incentivizing construction of CCS plants. Negative incentives can include carbon tax on fossil fuel emissions.

KEYWORDS

Carbon Capture and Storage (CCS)

Carbon Capture and Sequestration (CCS)

Natural gas

Methanol (MeOH)

Compressed Natural Gas (CNG)

Gas-to-Liquid (GTL)

Climate change

Carbon Dioxide (CO_2)

תפיסת ואחסון פחמן

גז טבעי

מתנול

שינוי אקלים

PLANNING VS EXECUTION

Month	Assignments	Execution
April 2017	Literature review	Completed
May 2017	Literature review	Completed
June 2017	Literature review	Completed
July 2017	CCS technologies comparison	Completed
August 2017	CCS technologies comparison	Completed
September 2017	CCS technologies comparison Preliminary Assessment of CCS potential during fuels production from natural gas	Completed
October 2017	Preliminary Assessment of CCS potential during fuels production from natural gas Preliminary Obstacles analysis	Completed
November 2017	Preliminary Assessment of CCS potential during fuels production from natural gas Preliminary Obstacles analysis	Completed
December 2017	Preliminary Recommendations	Completed
January 2018	Preliminary Recommendations Final report writing	Completed
February 2018	Final report writing	Completed
March 2018	Final report writing	Completed

ACRONYMS

BCM - Billion Cubic Meters

CCS - Carbon Capture and Storage / Carbon Capture and Sequestration

CCU - Carbon Capture and Utilization

CH_4 - Methane

CNG - Compressed Natural Gas

COE - Cost of Electricity

CO_2 - Carbon Dioxide

CO_2e - CO_2 equivalents (All greenhouse gases amounts are weighted by their global warming potentials for 100 years (GWP_{100}) to derive an equivalent CO_2 emissions value. This allows us to compare between different greenhouse gases on the same scale)

EOR - Enhanced Oil Recovery

EU - European Union

EV - Electric Vehicle

FCI - The Israeli Fuel Choices and Smart Mobility Initiative

GCCSI - Global CCS Institute

GHG - Greenhouse Gas

Gt - Gigatonne

GTL - Gas-to-Liquid

H_2 - Hydrogen

IEA - International Energy Agency

IGCC - Integrated Gasification Combined Cycle

ILS - Israeli New Shekel

IPCC - Intergovernmental Panel on Climate Change

LPG - Liquid Petroleum Gas

MeOH - Methanol

Mt, Mtpa - Millions of tonnes, Millions of tonnes per annum

MW, MWh – Megawatt, Megawatt hour

NDC - Nationally Determined Contribution

NGCC – Natural Gas Combined Cycle

NOx - Nitrogen Oxides

Petcoke - Petroleum coke: a final carbon-rich solid material that derives from petroleum refining

PPM - Parts per Million

R&D - Research and Development

SO_2 - Sulfur Dioxide

Syngas - "synthesis" natural gas

UNFCCC - United Nations Framework Convention on Climate Change

USD - United States Dollar

2DS - The 2°C Scenario (IEA, Energy Technology Perspectives)

1 INTRODUCTION

1.1 What is CCS?

Carbon Capture and Storage (CCS) is a process used to capture carbon dioxide (CO_2) emissions produced from the use of fossil fuels in industrial processes and electricity generation, and which aims to prevent the CO_2 from entering the atmosphere and mitigate the effect of greenhouse gases (GHGs) emissions on climate change.

Rather than being a single technology, CCS is a suite of technologies and processes. Some of these have been operated successfully for decades, while others are under development or in transition to large-scale application. Basically, CCS consists of three main stages:

- **Capture**, which is the separation of CO_2 from other gases produced from facilities including coal and natural gas power plants, steel mills and cement plants;
- **Transport**, where the CO_2 is moved, usually via pipelines, to a suitable site for deep underground storage, once it is separated and compressed; and
- **Storage** as the CO_2 is injected into deep underground rock formations or aquifers.

The CCS storage process simply imitates how nature has stored oil, gas and CO_2 for millions of years. The CO_2 can also be reused in processes such as enhanced oil recovery (EOR) or in the chemical industry, a process sometimes known as Carbon Capture and Utilization (CCU).

CCS is a vital technology for helping the world to meet the climate targets agreed at the 2015 Paris climate talks. The interest in CCS arises from three main factors:

1. A growing consensus that restricting serious climate change impacts must include extensive reductions in global CO_2 emissions, since CO_2 is the primary anthropogenic GHG, accounting for 77% of human contribution to the greenhouse effect in recent decades (Songolzadeh et al., 2014).
2. The understanding that broad emission reductions cannot be achieved easily or quickly by using less energy or by replacing fossil fuels with alternative energy sources that emit little or no CO_2. The world today relies on fossil fuels for over 85% of its energy use and changing that will take time. CCS thus offers a way to get large CO_2 reductions until cleaner, sustainable technologies can be widely deployed.

3. Energy-economic models show that adding CCS to the suite of other GHGs reduction measures significantly lowers the cost of mitigating climate change. Studies have also affirmed that by 2030, and beyond, CCS would be a major component of a cost-effective portfolio of emission reduction strategies (Folger, 2013).

CCS is only economical today in a limited number of situations. In addition to capital costs, currently available technologies for CCS at power plants, for example, impose an energy penalty by requiring additional energy to operate the CO_2 capture and compression equipment. In some cases, a relatively pure stream of CO_2 in a natural gas feed or conversion process can be captured and used economically.

It is well recognized that deployment of CCS on a scale that makes a material contribution to reducing CO_2 emissions requires addressing current barriers, including: cost, complexity along the value chain, regulatory/policy uncertainty, public acceptance, large-scale storage sites and long-term liability issues.

1.2 Emergence of CCS

CCS first emerged on the international agenda at the Gleneagles G8 summit in Scotland in 2005, leading to a program of work for the International Energy Agency (IEA) and to several countries seeking to rollout CCS technologies.

The scientific credibility of CCS was enhanced by the 2005 Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) and supported by the IEA. However, until 2009, CCS seemed to have been limited mainly by its use for EOR, with the potential for enhanced storage in depleted reservoirs in the context of the increasingly prominent climate agenda.

The failed climate change summit in Copenhagen in 2009 seems to have impacted the perception of CCS (UNFCCC, 2009). Without global consent that climate change mitigation that must be taken seriously when considering investment decisions, industry found little reason to invest in deploying CCS on a large scale since it adds significantly to the cost of power generation and to manufacturing products utilizing fossil fuels. Similarly, in the absence of an appropriate climate policy, decision makers considered capturing, storing, or using anthropogenic CO_2 only when CCS seems to make economic sense in applications such as in EOR in combination with CO_2 sources that are already of high purity. Since the Copenhagen summit the factors affecting CCS deployment have become more diverse and complex, including CO_2 price and the use of coal as the primary fuel to generate electricity. More recently, however, the success of renewables and the availability of shale oil, and in particular shale gas in North America, have made coal seem less crucial. Yet, because coal is more easily transportable and gas, generally, is not, the drop-in coal use in the United States has led to lower prices and an increased use of coal elsewhere in the world.

The international agreement on climate change adopted in Paris in December 2015, known as the Paris Agreement (UNFCCC, 2015), represents a clear and indisputable commitment from the world's political leaders to transition to a low-carbon economy. The agreement defines a number of climate goals:

1. A short-term goal to reach peak emissions and start to reduce them as soon as possible in order to meet the longer- term temperature set goals.
2. A longer- term goal to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.
3. At the same time, increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low GHG emissions development, in a manner that does not threaten food production.

Limiting the long-term rise in average global temperature to 2°C would require a substantial reduction in CO_2 emissions from present levels, not just a slowing in emissions growth. The approach adopted in the Paris Agreement for the post-2020 climate change convention is fundamentally different from that of the pre-2020 agreement under the Kyoto Protocol. The approach developed is more of a 'bottom-up' approach that allows countries to establish their Nationally Determined Contribution (NDC) allowing for greater national level determination of future climate actions for both developed and developing countries (UNFCCC, 2016).

There are those who claim that CCS will never make a significant contribution to solving the climate problem, or worse, will distract from making needed decisions to begin phasing out fossil fuels immediately (de Coninck & Benson, 2014). It should be noted that renewables and energy efficiency alone cannot deliver climate outcomes consistent with the Paris Agreement. According to the IEA modelling, CCS could deliver 13% of the cumulative emissions reductions needed by 2050 to limit the global increase in temperature to 2°C (IEA 2DS -2°C Scenario) (IEA, 2015b), as depicted in Figure 1-1.

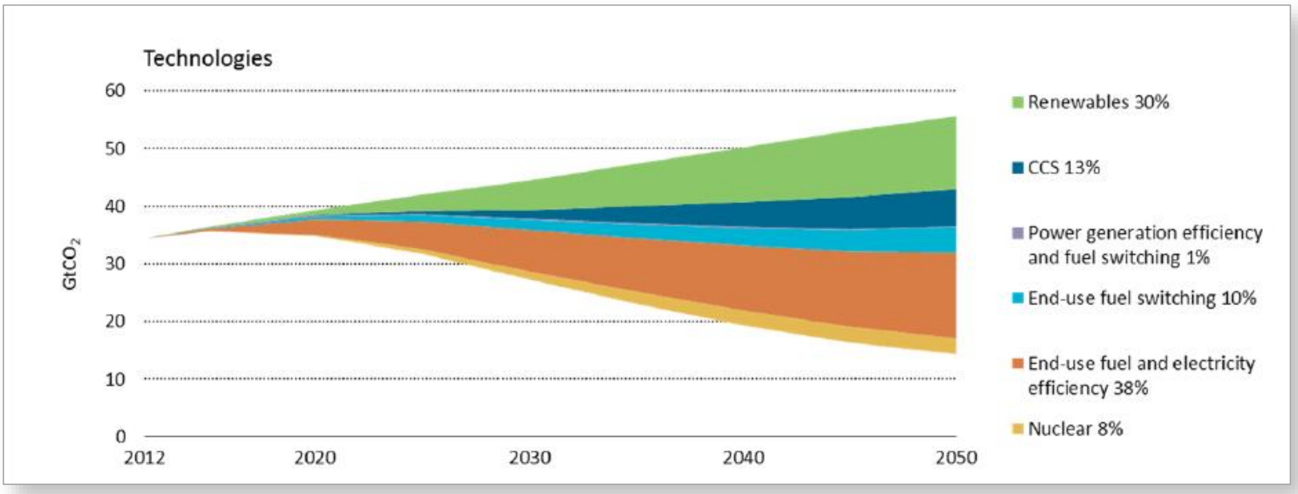


Figure 1-1 > Contribution of technologies and sectors to global cumulative CO_2 reductions (IEA, 2015b – Figure 1.6)

The IPCC indicates that without CCS, the cost of achieving atmospheric concentrations of 450 parts per million (ppm) of CO_2 equivalent (CO_2e) by 2100 could be 138 per cent more costly (compared to scenarios that include CCS). There are only a minority of climate model runs that successfully produce a 450 ppm scenario in the absence of CCS (IPCC, 2014).

One of the major benefits of CCS as an emissions reduction technology is that it can be applied to different types of CO_2 emission sources, particularly those with very large volumes of emissions, such as power plants and some industrial facilities. Fossil fuels are essential to the production process of many vital industries such as the steel, cement and chemical industries. Fossil fuels are utilized in these industries because of their chemical and physical properties and are also being used as a feedstock to industrial processes, and not merely as a primary energy source to generate electricity.

Just as the use of fossil fuels in power production generates large volumes of CO_2, so too does the use of fossil fuels in industrial applications. However, unlike in power generation, for industrial use fossil fuels are used as feedstock and not merely for process heat. Therefore, it is currently not feasible to substitute all fossil fuels used in industry by renewable energy sources in order to reduce emissions. As a result, aside from the application of energy-efficiency measures, CCS is the only large-scale technology available that can help achieve deep reductions in CO_2 emissions in the long term from many industrial processes.

1.3 Israel's current and future transportation fuel mix

The Israeli transportation sector is entirely dependent on oil-derived fuels, with final consumption amounting to 3,103 and 2,702 thousand Tons of Oil equivalent (TOE) of gasoline and diesel, respectively, in 2016 (CBS, 2018); in addition, an unknown share of the 615 thousand tons of Liquid Petroleum Gas (LPG) total consumption (MOE, 2018) is directed to private vehicles which went through aftermarket conversion into dual-fuel fueling system, although uptake of LPG for transportation is arguably quite limited. The vast majority of the domestic demand is met by local refining carried in Israel's two refineries, using all-imported crude oil. However, where surplus diesel refining capacity sees roughly 40% of production directed to export, recently local fuel providers opted to shift some of their procurement to imported gasoline, estimated to gain about 15% market share for that fuel type (Gutman, 2017).

The Israeli government seeks to transition the transportation sector to alternative sources of energy, with the goals of reducing the share of oil in Israel's transportation by 30% until 2020 and by 60% in 2025 (PMO, 2013). The alternative energy sources are expected to consist of a mix of bio fuels, electricity and natural-gas derived fuels including Compressed Natural Gas (CNG), methanol (MeOH) and Gas-to-Liquid (GTL) diesel replacement (see Figure 1-2).

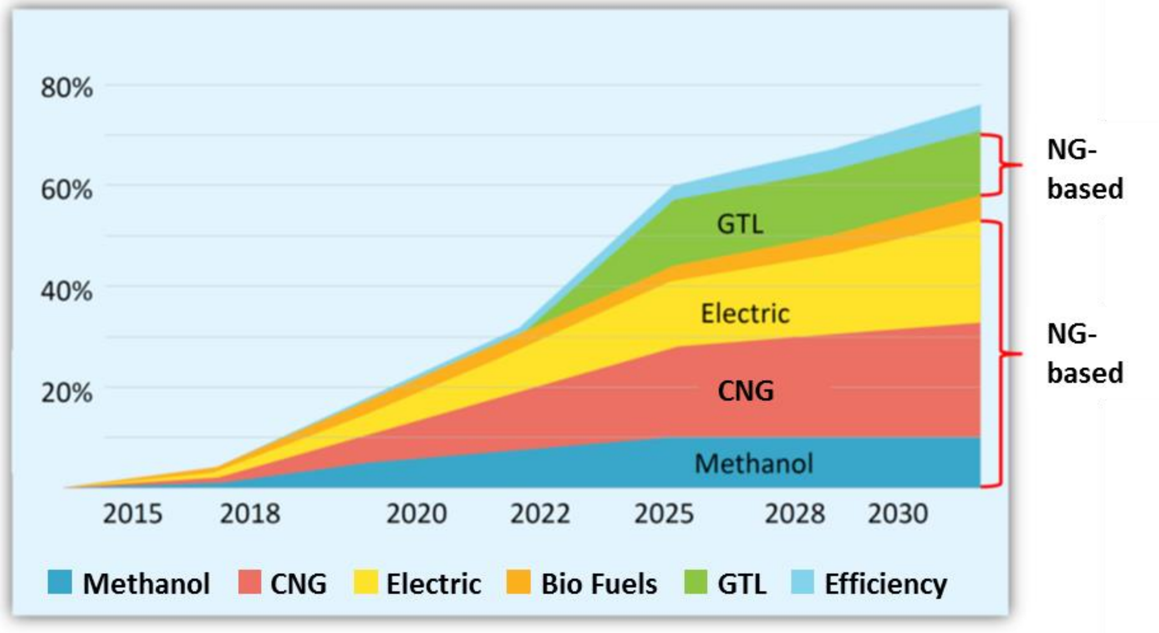


Figure 1-2 > Expected penetration rate for alternative fuels in Israel (FCI, 2016)

Earlier formal predictions for natural gas demand through 2030 estimate up to 4.0 Billion Cubic Meter (BCM) per year would be directly demanded by the transportation sector, together with MeOH and ammonia production (0.7 BCM), amounting to a total 39 BCM of natural gas by 2030; increase in demand for NG by the electricity sector is also partially attributed to expected increase in electricity consumption used for transportation (see Figure 1-3).

Figure 1-3 > Projected trends of natural gas consumption in Israel for the years 2014 – 2040 (MOE, 2012a)

Recently the Ministry of Energy (MOE) publicly expressed its policy to fully withdrawal from diesel and gasoline use in Israel by 2030 (Gutman, 2018), backed by regulatory actions and budget allocations to facilitate increase in the share of electricity and natural gas-based transportation, through several supportive schemes for infrastructure deployment. Whereas electric vehicles (EVs) are mainly targeted at the private cars, city buses and rail segments, natural gas is set as the alternative fuel of choice for trucks and as a diesel-replacement via GTL.

1.4 Research goals

The research study described in this report is a comparative study of the carbon capture alternatives in the production of natural gas-based transportation fuels in Israel, along with its utilization and/or storage potential.

According to the IPCC fifth assessment report, the transportation sector is responsible for about 15% of global anthropogenic emissions of GHGs (IPCC, 2014). In Israel, land transportation contributes a high percentage to the overall CO_2 emissions. The Israeli Central Bureau of Statistics (IL-CBS) notes that in 2014 out of about 60.9 million tons of overall CO_2 emissions from fuels combustion, 15.6 million, or about 26 percent, are attributable to land transportation (excluding rail) (IL-CBS, 2015).

The national Fuel Choices Initiative in Israel (FCI) plans to address the absolute reliance of the transportation sector on petroleum products, and to diversify the fuel mix. The major source of these alternative transportation fuels is based on natural gas - whether as CNG, various MeOH blends, GTL processes, or electric transportation (that will rely mainly on natural gas power plants) (FCI, 2016). Today, 25% of Israel's national plan to reduce GHG emissions relies on transformation to natural gas use as a primary energy source. One aspect of this transformation is the use of natural gas as a source for transportation fuels (MOEP, 2015). One of the major options to reduce GHG emissions while still using fossil fuels is CCS. Without CCS, even the transformation to natural gas instead of coal and petroleum as a major energy source would not be enough to reduce GHG emissions substantially.

If production plants for manufacturing natural gas-based transportation fuels are built in Israel, CCS technologies could be implemented in them as well as in power plants, to help further reduce the national GHG emissions. As Israel plans to transform its transportation sector to rely heavily on natural gas in the coming decades, there is a need to find ways to continue and reduce GHG emissions in order to comply with the 2015 Paris Agreement.

The research goals of this work are as follows:

1. To review the status of the CCS field in the world,
2. To compare between different CCS technologies and their relevance to the production of natural gas-based fuels in Israel,
3. To compare between implementation of CCS in power plants (electric fuel) and in fuels production in chemical synthesis plants,
4. To assess the potential for CCS implementation during fuels production (including electricity) from natural gas in Israel,
5. To analyze the obstacles for CCS implementation, along with natural gas-based fuels production, in Israel,
6. To propose policy recommendations on the topic to the Ministry of Environmental Protection.

In this final report we provide in Chapter 2 below a background of the CCS field, followed by a description of the degree of maturation of the CCS technologies in Chapter 3, and a policy overview in Chapter 4. Chapter 5 presents a preliminary assessment of CC potential during fuels production from natural gas in Israel, and Chapter 6 is a key findings and recommendations for Implementation in Israel.

2 BACKGROUND OF THE CCS FIELD

2.1 Technical basis

In CCS, the CO_2 produced from carbon in the fossil fuels or biomass feedstock is first captured, and then compressed to a dense liquid to facilitate its efficient transport and storage, as depicted schematically in Figure 2-1.

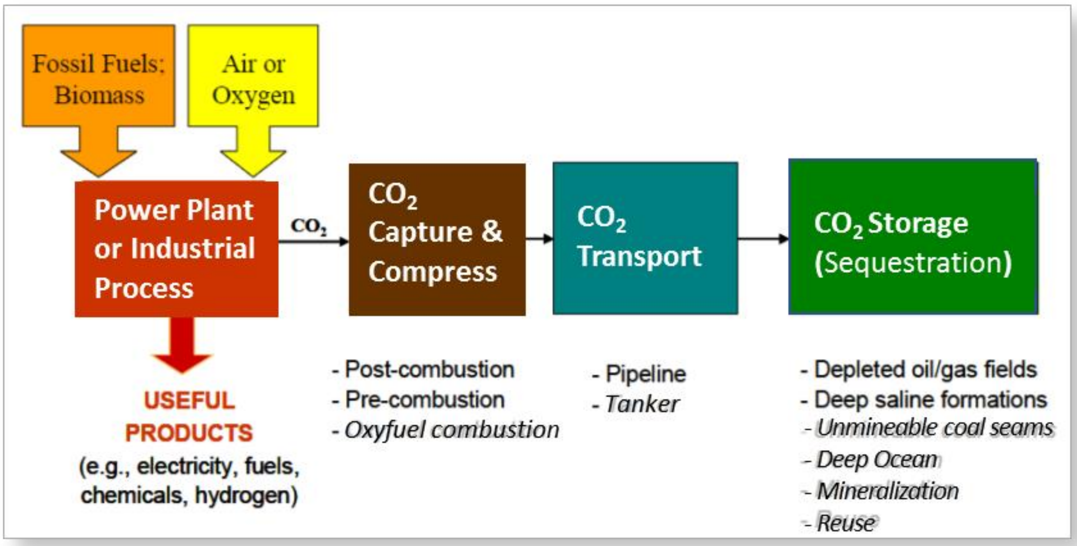


Figure 2-1 > Schematic of a CCS System consisting of CO2 Capture, Transport and Storage (Rubin, 2010)

The CCS operation's chain consists of three parts:

- **Capturing CO_2** where various technologies may be used to allow the separation of CO_2 from gases produced in electricity generation and industrial processes by one of three methods: pre-combustion, post-combustion and oxyfuel combustion.
- **Transportation of CO_2** for safe storage by either road tankers (for small amounts only), pipeline (the most common way) or by ship (used for offshore CO_2 generation).
- **CO_2 storage** in carefully selected geological rock formations (depleted oil and gas fields or deep saline aquifer formations) that are typically located several kilometers below the earth's surface.

At every point in the CCS chain, from production to storage, there are a number of process technologies that are well understood and have excellent health and safety records, as will be described below. The commercial deployment of CCS involves the widespread adoption of these CCS techniques, combined with robust monitoring techniques and government regulations.

2.2 CO_2 Capture

A variety of technologies for separating (and capturing) CO_2 from a mixture of gases are commercially available and are widely used today, typically as a purification step in an industrial process (Folger, 2013). The environmental aspects of these technologies are elaborated in Chapter 4.2. The choice of technology depends on the type of source, the cost, and the requirements for product purity and on the conditions of the gas stream being treated (such as its temperature, pressure, and CO_2 concentration). Figure 2-2 illustrates the variety of technical approaches available, including absorption into physical and chemical solvents, adsorption onto solid substrates, cryogenic separation, diffusion through CO_2 selective membranes, and mineralization.

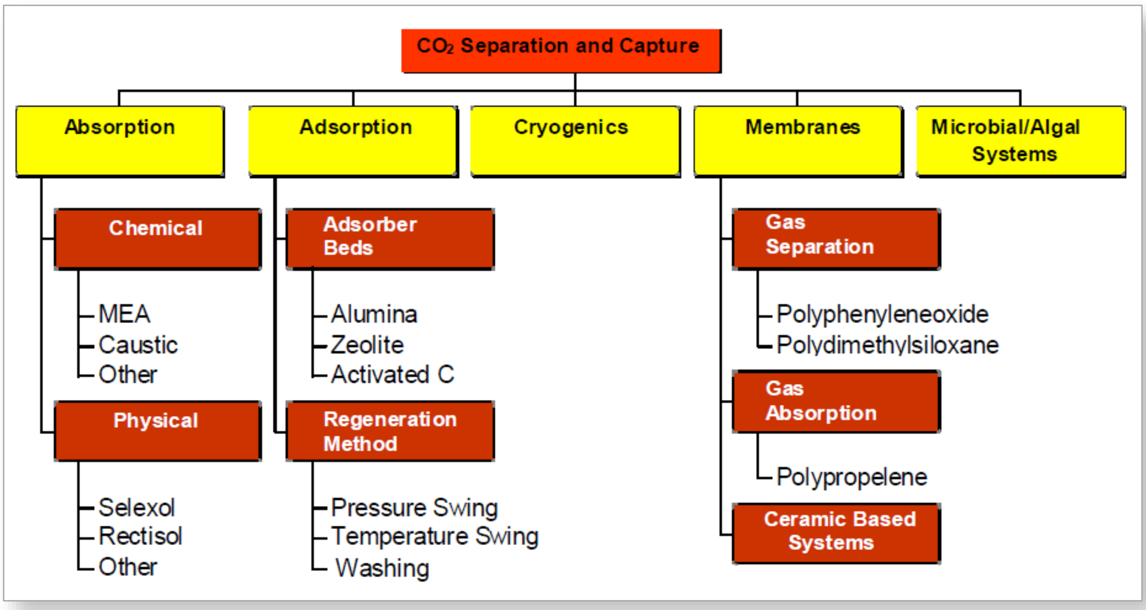


Figure 2-2 > Technical options for CO_2 capture
(Rao & Rubin, 2002)

Since most anthropogenic CO_2 is a by-product of the combustion of fossil fuels, CO_2 capture technologies are commonly classified as either pre-combustion or post-combustion systems, depending on whether carbon (in the form of CO_2) is removed before or after a fuel is burned, as described in Figure 2-3. A third approach, called oxyfuel or oxy-combustion, which combusts CO_2 into pure oxygen or a mixture of oxygen and CO_2, does not require a CO_2 capture device, but requires separation of oxygen from air using cryogenic separation.

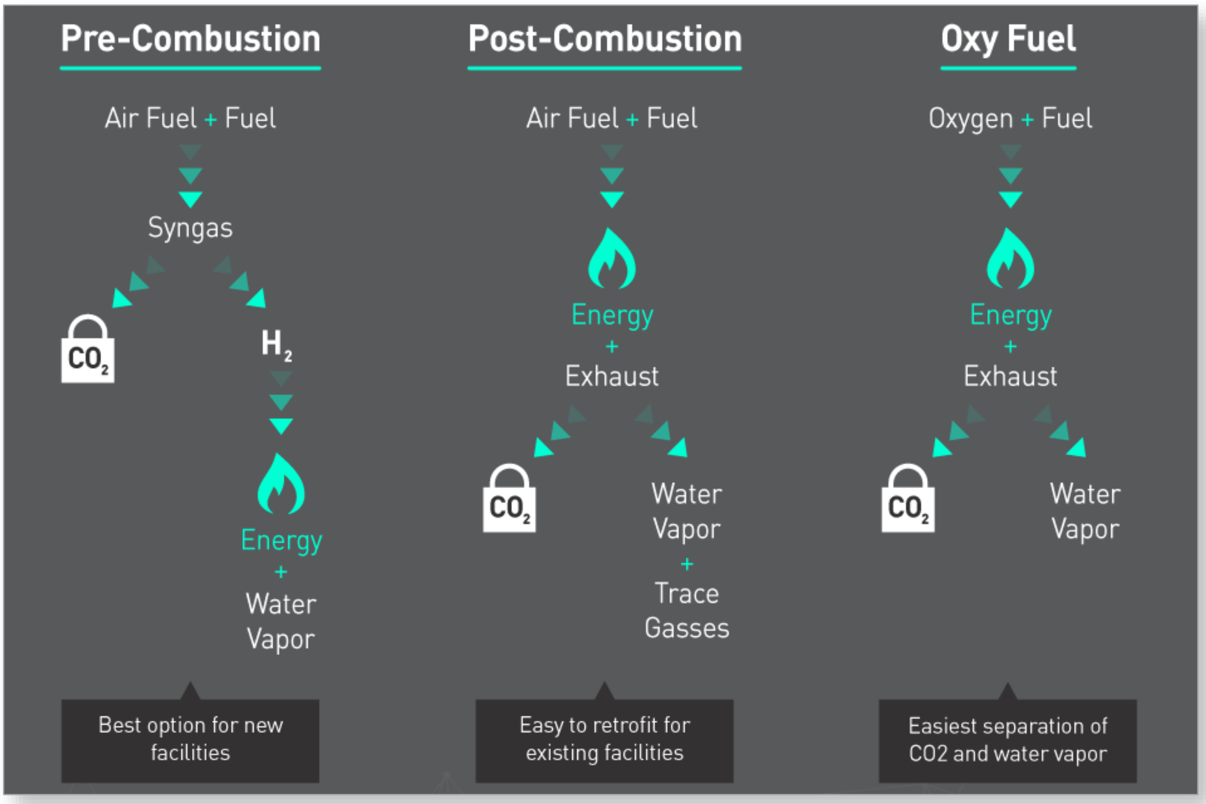


Figure 2-3 > Three schemes for carbon capture done in conjunction with power generation (Futurism, 2018)

Other industrial processes that do not involve combustion employ the same types of CO_2 capture systems that would be employed at power plants.

Today most CO_2 separation uses absorption-based technology. For natural gas cleanup, cryogenic separation and membrane separation are used, albeit on a limited basis. In all cases, the aim is to produce a stream of pure CO_2 that can be permanently stored or sequestered. The captured CO_2 is first typically compressed to a dense “supercritical” state, where it behaves as a liquid that can be readily transported via pipelines or tankers. The CO_2 compression step is commonly included as part of the capture system, since it is usually located at the industrial plant site where CO_2 is captured. Figure 2-4 provides a general depiction of CO_2 capture routes (IPCC, 2005).

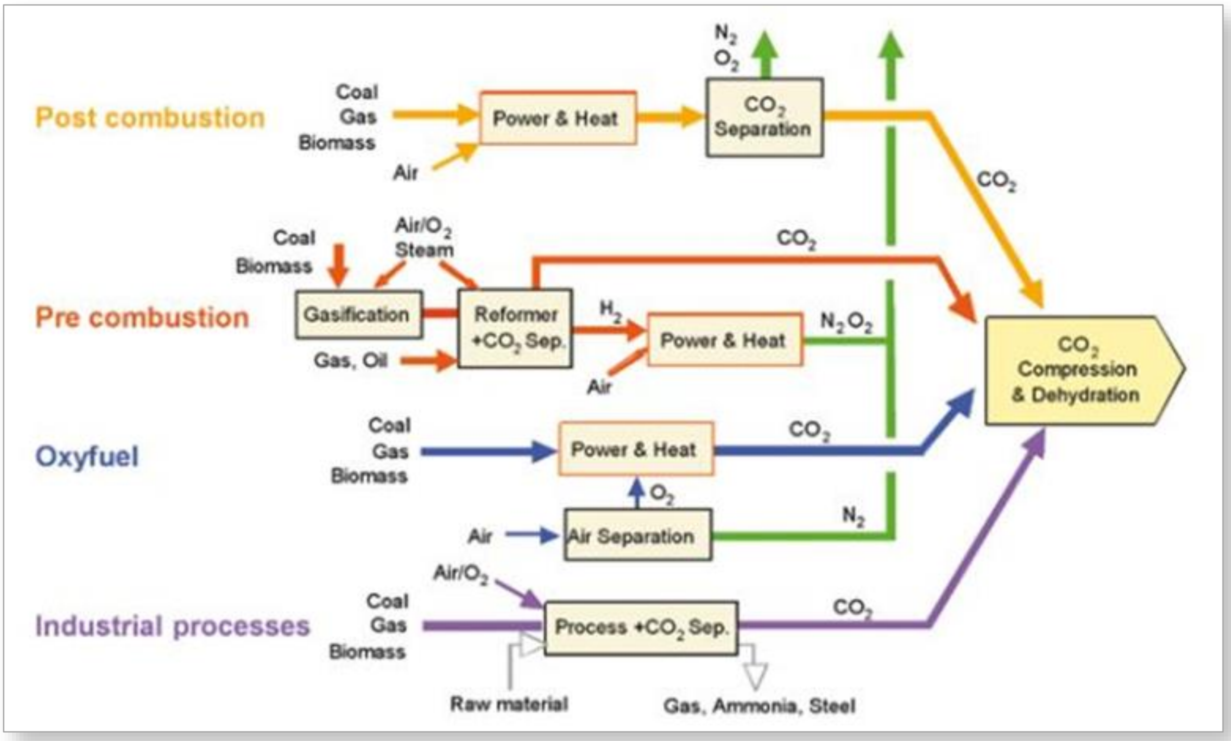


Figure 2-4 > CO_2 capture routes
(IPCC, 2005)

2.2.1 Post-Combustion Processes

As the name implies, these systems capture CO_2 from the flue gases produced after fossil fuels or other carbonaceous materials (such as biomass) are burned. Combustion-based power plants provide most of the world’s electricity today. In a modern coal-fired power plant, pulverized coal (PC) is mixed with air and burned in a furnace or boiler. The heat released by the combustion process generates steam, which drives a turbine-generator. The hot combustion gases exiting the boiler consist mainly of nitrogen (from air) plus smaller concentrations of water vapor and CO_2 formed from the combustion of the hydrogen (H_2) and carbon in the fuel. Additional products formed during combustion from impurities in coal include sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (fly ash). These regulated air pollutants, as well as other trace species such as mercury, must be removed to meet applicable emission standards. In some cases, additional removal of pollutants (especially SO_2) is required to provide a sufficiently clean gas stream for subsequent CO_2 capture.

With current technology, the most effective method of CO_2 capture from the flue gas of a PC plant is by chemical reaction with an organic solvent such as mono-ethanol-amine (MEA), one of a family of amine compounds. In a vessel called an absorber, the flue gas is “scrubbed” with an amine solution, typically capturing 85% to 90% of the CO_2. The CO_2-laden solvent is then pumped to a second vessel, called a regenerator, where heat is applied (in the form of steam) to release the CO_2. The resulting stream of concentrated CO_2 is then compressed and piped to a storage site, while the depleted solvent is recycled back to the absorber. This technology is also used to capture CO_2 for use in the food and beverage industry and as a raw material in fertilizer manufacturing.

A large number of new processes and materials for post-combustion CO_2 capture are currently at the laboratory or bench-scale stage of development. These can be grouped into three general categories (Folger, 2013):

- **Liquid solvents** (absorbents) that capture CO_2 via chemical or physical mechanisms – the liquid solvents (typically a mixture of a base and water) selectively absorb CO_2 through direct contact between the chemical solvent and the flue gas stream. Regeneration of the solvent and release of CO_2 then takes place in a separate vessel (the regenerator) through a change of process conditions, such as a swing in temperature or pressure. Advanced amines, Potassium carbonate, advanced mixtures and Ionic liquids are the main approaches being pursued in this category.

- **Solid adsorbents** that capture CO_2 via physical mechanisms - solid sorbents capture (adsorb) CO_2 on their surfaces. They then release the CO_2 through a subsequent temperature or pressure change, thus regenerating the original sorbent. Solid sorbents have the potential for significant energy savings over liquid solvents, in part because they avoid the need for the large quantities of water that must be repeatedly heated and cooled to regenerate the solvent solution. Sorbent materials also have lower heat capacity than solvents and thus require less regeneration energy to change their temperature. Examples for Solid adsorbents being tested include: Supported amines, Carbon-based, Sodium carbonate and Crystalline materials.

- **Membranes** that selectively separate CO_2 from other gaseous species – the membranes are porous materials that can be used to selectively separate CO_2 from other components of a gas stream. They effectively act as a filter, allowing only CO_2 to pass through the material. The driving force for this separation process is a pressure differential across a membrane, which can be created either by compressing the gas on one side of the material or by creating a vacuum on the opposite side. Polymeric, Amine-doped, integrated with absorption and Biomimetic based membranes are included in this category.

2.2.2 Pre-Combustion Processes

Pre-combustion uses steam and air or oxygen to convert fuel into a mixture of mainly H_2 and CO_2. To remove carbon from fuel prior to combustion, it must first be converted to a form amenable to capture. For coal-fueled plants, this is accomplished by reacting coal with steam and oxygen at high temperature and pressure, a process called partial oxidation, or gasification. The result is a gaseous fuel consisting mainly of carbon monoxide (CO) and H_2—a mixture known as "synthesis" gas (syngas)—which can be burned to generate electricity in a combined cycle power plant. This approach is known as integrated gasification combined cycle (IGCC) power generation. After particulate impurities are removed from the syngas, a two-stage “shift reactor” converts the CO to CO_2 via a reaction with steam (H_2O). The result is a mixture of CO_2 and H_2. A chemical solvent, such as the widely used commercial product Selexol[2] (which employs a glycol-based solvent), then captures the CO_2, leaving a stream of nearly pure H_2 that is burned in a combined cycle power plant to generate electricity.

Although the fuel conversion steps of an IGCC plant are more elaborate and costly than traditional coal combustion plants, the pressure and concentration of CO_2 obtained through pre-combustion is relatively high, making separation easier and cheaper to achieve. Thus, rather than requiring a chemical reaction to capture CO_2 (as with amine systems in post-combustion capture), the mechanism employed in pre-combustion capture involves physical adsorption onto the surface of a

---

[2] The UOP Selexol™ - https://www.uop.com/processing-solutions/gas-processing-2/synthesis-gas-treating/acid-gas-removal/

solvent, followed by release of the CO_2 when the sorbent pressure is dropped, typically in several stages.

Pre-combustion capture also can be applied to power plants using natural gas. As with coal, the raw gaseous fuel is first converted to syngas via reactions with oxygen and steam—a process called reforming. This is again followed by a shift reactor and CO_2 separation, yielding streams of concentrated CO_2 (suitable for storage) and H_2. This is the dominant method used today to manufacture H_2. If the H_2 is burned to generate electricity, as in an IGCC plant, we have pre-combustion capture. While pre-combustion CO_2 capture is usually more costly than post-combustion capture for natural gas-fired plants, some power plants of this type have been proposed.

Pre-combustion has been used for many years in the industrial production of ammonia and H_2. However, the fuel conversion steps required are relatively complex, making pre-combustion more suitable for use in new-built plants rather than retrofitting of existing plants.

Although pre-combustion CO_2 capture has a lower energy penalty and lower cost than post-combustion capture processes performing a similar task, there is scope for further improvements that can reduce costs. With this aim, current research is focused mainly on improving the capture efficiency so that the size and cost of equipment can be lowered. Current research is focused on the same three approaches discussed for post-combustion capture technologies, namely, liquid solvents, which separate CO_2 from a gas stream by selective absorption (research on physical solvents is aimed at improving the CO_2 carrying capacity and reducing the heat of absorption); solid sorbents, which separate CO_2 by adsorption onto the solid surface; and membranes, which separate CO_2 by selective permeation through thin layers of solid materials.

2.2.3 Oxy-Combustion Systems

Oxy-combustion (or oxyfuel) systems are being developed as an alternative to post-combustion CO_2 capture for conventional coal-fired power plants. Here, pure oxygen rather than air is used for combustion. This eliminates the large amount of nitrogen in the flue-gas stream. After the particulate matter (fly ash) is removed, the flue gas consists only of water vapor and CO_2, plus smaller amounts of pollutants such as SO_2 and NO_x. The water vapor is easily removed by cooling and compressing the flue gas. Additional removal of air pollutants leaves a nearly pure CO_2 stream that can be sent directly to storage.

The principal attraction of oxy-combustion is that it avoids the need for a costly post-combustion CO_2 capture system. Instead, however, it requires an air separation unit (ASU) to generate the relatively pure (95%-99%) oxygen needed for combustion. Roughly three times more oxygen is needed for oxyfuel systems than for an IGCC plant of comparable size, so the ASU adds significantly to the cost. Typically, additional flue gas processing is also needed to reduce the concentration of conventional air pollutants, to comply with applicable environmental standards, or to prevent the undesirable buildup of a substance in the flue gas recycle loop, or to achieve pipeline CO_2 purity specifications (whichever requirement is the most stringent). Because combustion temperatures with pure oxygen are much higher than with air, oxy-combustion also requires a large portion (roughly 70%) of the inert flue gas stream to be recycled back to the boiler to maintain normal operating temperatures. To avoid unacceptable levels of oxygen and nitrogen in the flue gas, the system also has to be carefully sealed to prevent any leakage of air into the flue gas. This is a challenge since such leakage commonly occurs at existing power plants at flanges and joints along the flue gas ducts, especially as plants age. Although in principle oxyfuel systems can capture all of the CO_2 produced, the need for additional gas treatment systems decreases the capture efficiency to about 90% in most current designs.

2.3 CO_2 storage

Over the years, several options for storage of captured CO_2 have been assessed, including ex situ mineralization, ocean storage in a dissolved or liquid form, reuse in the chemical industry, and sequestration in deep geological formations (IPCC, 2005). Of these options, today only storage in geological formations is considered to have the capacity, permanence, and environmental performance necessary for CO_2 storage at the gigatonne (Gt) scale needed to materially reduce CO_2 emissions. Deep geological formations suitable for CO_2 storage typically occur in sedimentary basins and include depleted or depleting oil and gas reservoirs and saltwater-filled rocks (so-called saline formations). In these geological formations, CO_2 is injected at depths of 800 m or more where, under typical conditions, CO_2 has a liquid-like density in the range of 500 to 700 kg/m^3. The liquid-like density is important from the perspectives of efficiently using the underground storage space and of minimizing the buoyancy forces that would cause leakage back to the atmosphere.

Sand layers provide storage space for oil, water, and natural gas. Silt, clay, and evaporite (rock formations composed of salt deposited from evaporating water) layers provide seals that can trap these fluids underground for millions of years and longer. For oil and gas reservoirs, which are found under such fine-textured rocks, the mere presence of oil and gas demonstrates the presence of a reservoir seal. For saline formations, a significant site characterization effort is required to demonstrate the presence of a satisfactory seal. Important attributes of the seal include low permeability (10–18 m^2 or less) and a high capillary entry pressure (1 Megapascal (MPa)[3] or more).

To increase the diversity of options for geological storage of CO_2, several ongoing studies are evaluating the potential of CO_2 storage in basalt formations, which rely on geochemical reactions between the CO_2 and basalt to store CO_2 underground as a mineral such as calcite or magnesite and coal beds where CO_2 is adsorbed to the solids (Aradóttir et. al., 2011; IEA, 2016a; IPCC, 2014; Mc Grail et. al., 2006; Oelkers et. al., 2008). A summary of the key characteristics for the three types of storage sites is provided in Table 2-1.

---

[3] MPa - one million pascal unit or 10 Bars

Table 2-1 > Summary of characteristics for CO_2 storage

	Depleted hydrocarbon fields	Deep saline aquifers	Coal seams / Basalt formations
World storage capacity	1,000 Gt CO_2, geographically limited to hydrocarbon-rich regions of the world	1,000 to 10,000 Gt CO_2, uncertainty about how much of this capacity can be utilized	
Injection depth	800 m or more	800 m or more	Coalbed - 300 to 600 m
CO_2 density	500 to 700 kg/m^3	500 to 700 kg/m^3	CO_2 adsorbed to the solids or stored as a mineral such as calcite or magnesite
Reservoir seal	Silt, clay, and evaporite. the mere presence of oil and gas demonstrates the presence of a reservoir seal	Silt, clay, and evaporite. satisfactory seal includes low permeability (10–18 m^2 or less) and a high capillary entry pressure (1 MPa or more)	
Advantages	Use for EOR		Enhanced coalbed methane production (Llamas et al., 2016)

Geological storage of CO_2 has been successfully demonstrated at a number of pilot and large-scale sites over the last two decades in both onshore and offshore environments. The injection of CO_2 underground was not totally new when it was first suggested for climate change mitigation. In the 1970s and 1980s, as production from oil fields in the United States was declining, oil companies started injecting water, natural gas, and CO_2 to recover more oil and extend the productive lifetime of oil reservoirs. Thousands of kilometers of CO_2 pipelines were constructed to transport the CO_2 from the natural reservoirs of CO_2, the primary CO_2 source, to the depleting oil fields. CO_2 EOR was done almost exclusively using CO_2 from natural underground CO_2 reservoirs, so it was not leading to climate change mitigation.

Combining Enhanced Oil Recovery (EOR) with CO_2 storage

In CO_2-EOR the majority of the injected gas remains in the reservoir and the portion that re-emerges with the produced oil is separated from the oil and re-injected in a closed loop. Combining EOR with permanent CO_2 storage, or "EOR+", *represents a significant win-win opportunity. According to IEA analysis, EOR+ could theoretically store around 240 Gt of CO_2 – more than twice the storage required in the IEA 2DS – while increasing global oil production by as much as 375 billion barrels by 2050.*

Today's CO_2-EOR operations are carried out with the primary objective of maximizing oil output with limited or no focus on CO_2 storage. Moving to an EOR+ model, with a dual objective of permanent CO_2 storage, will require a shift from current practice and involve taking on additional activities associated with monitoring and verification of the stored CO_2. The emissions reduction benefit of EOR+ is tempered by the production of additional fossil fuels from which the majority of the carbon is inevitably emitted back to the atmosphere. However, IEA analysis indicates that using CO_2 in EOR+ projects can generate net emission reductions.

This accumulated experience has resulted in well-established best practices and techniques required to select, safely operate and close (secure) CO_2 storage sites. There are three basic technical requirements for storage sites:

1. **Containment** – Storage sites need to be capable of securely storing CO_2 in subsurface reservoirs with low and manageable risks, including those associated with any potential leakage.
2. **Capacity** – Storage sites need subsurface reservoirs that can permanently store the required amounts of CO_2.
3. **Injectivity** – Storage sites require subsurface reservoirs that can accept CO_2 at an appropriate rate in relation to the capture process at the relevant industrial source(s).

CCS investments will require a high level of certainty that sufficient storage capacity is available and can be accessed at a reasonable cost before making a final investment decision. For 'greenfield' storage sites, this process can take close to a decade. While appropriate site selection and characterization are critical, a key part of this process will also be effective community engagement, recognizing that there may be a low level of awareness and acceptance of CO_2 storage amongst local communities.

There is an abundance of geological formations suitable for CO_2 storage globally. Oil and gas reservoirs are anticipated to have on the order of 1,000 Gt CO_2 storage capacity (Benson et. al., 2012). But they are geographically limited to hydrocarbon-rich regions of the world, and they may not be available for storage until the oil and gas reservoirs are fully depleted or until market conditions favor CO_2-enhanced oil or gas recovery. Saline aquifers, which are the common option for carbon storage today, are assessed to have the largest storage capacity with global estimates ranging from 1,000 to 10,000 Gt CO_2 (IEA, 2016a; IPCC, 2014).

2.4 Examples of currently operating CCS projects

CCS has been applied in a wide range of industries since 1972. AS of 2017, seventeen large scale facilities[4] are operating successfully around the world (with 4 more coming on-stream shortly, 5 facilities in advanced development, and another 11 facilities in earlier stages of development worldwide). These 17 facilities are currently capable of capturing more than 30 Mtpa of CO_2 and facilities under development could increase this capacity to 69 Mtpa. In addition, there are around 15 smaller scale CCS facilities[5] in operation or under construction around the world. In total, these facilities can capture over 2 Mtpa of CO_2 (GCCSI, 2017). However, 3,800 Mtpa of CO_2 need to be captured and stored, or around 2,500 of CCS facilities must be operating in 2040 if the Paris 2˚C target is to be achieved.

In addition, in the past few years several projects had been postponed or cancelled, and the projects pipeline has been drying up (from 65 potentials facilities down to 48 in the period of 2013 to 2016) (IPIECA, 2018).

Table 2-2 shows the number and regional distribution of large-scale CCS facilities.

---

[4] Large-scale CCS facilities are facilities with annual CO_2 capture capacity of 400,000 tons or more

[5] The CO_2 capture capacity of these individual facilities ranges from around 50,000 to almost 400,000 tonnes per annum.

Table 2-2 > Large-scale CCS facilities by region

	Operating	In Construction	Advanced Development	Early Development	Total
Americas					
United States	9		2		11
Canada	3	2			5
Brazil	1				1
Asia Pacific					
China		1	1	6	8
Australia		1	1	1	3
South Korea				2	2
Europe					
Norway	2		1		3
UK				2	2
Middle East					
Saudi Arabia	1				1
United Arab Emirates	1				1
Total	17	4	5	11	37

(Source: GCCSI, 2017)

Enhanced oil recovery using CO_2 (CO_2-EOR)

EOR has been a major driver of many early CCS projects, providing a revenue stream for the captured CO_2. In the United States, CO_2 has been used for EOR for several decades, facilitated by an existing network of CO_2 transport pipelines which span more than 6,600 km.

In North America and in the Middle East in particular, there is potential to expand the use of EOR for climate change purposes by combining it with permanent CO_2 storage. This requires that EOR projects implement measures to verify that the CO_2 remains underground.

Power plant CCS projects

Gas-fired power: CCS applied to gas-fired power generation can play an important role in a global climate change response. In regions with low gas prices, such as the United States, advancing CCS on gas-fired power might be more favorable than for coal.

Coal-fired power: Fuel cost issues in the power sector are key drivers and CCS on coal-fired power may turn out to be particularly attractive in the Asian market, including substantial retrofitting opportunities in China.

There are few power plant CCS projects around the world:

- SaskPower's Boundary Dam, Canada - The world's first commercial-scale CCS plant applied to coal-fired power generation, commenced operation in 2014. The project is owned by Canadian utility firm SaskPower and is reducing CO_2 emissions from 1,100 to 120–140 t/MWh, from a 110 MW coal unit that has been retrofitted with CCS technology. The project will eventually capture 1 million tonnes of CO_2 annually from the power station's stack. The power station has a number of other coal units where carbon will not be captured – it has a total capacity of 824 MW and its total emissions are 6.7 million tonnes. With CCS, 15 per cent of the power station's total emissions are captured.
- Kemper County, Mississippi, US - The Kemper County coal CCS plant is a completely new power plant using pre-combustion carbon capture. This means it will turn coal into a mixture of hydrogen and carbon dioxide, burning the hydrogen to generate power and capturing the carbon for EOR. The project intends to capture about 65 per cent of emissions – around 3.5 million tonnes a year. In October 2016 the plant produces electricity using syngas in first of two gasifiers, however, in June 2017 the plant suspended the coal gasification, due to low natural gas prices.
- Petra Nova CCS project, Texas, US - The Petra Nova project, operational since January 2017, is the world's largest post-combustion CO_2 capture system presently in operation. Production unit 8 of the W. A. Parish power plant near Houston, Texas, was retrofitted with a 1.4 Mtpa post-combustion CO_2 capture facility. The CCS system is designed to capture about 90% of the CO_2 emitted from the flue gas slipstream, or about 33% of the total

emissions from Unit 8. The captured CO_2 is transported via pipeline to an oil field near Houston for EOR.

CCS with bioenergy (BECCS)

Offers permanent net removal of CO_2 from the atmosphere, or "negative emissions" by using biomass that has removed atmospheric carbon while growing, and then storing the emissions from combustion, underground. The Illinois Industrial CCS Project is operating since April 2017. This is the world's first large-scale BECCS project, as well as the first CCS project in the US to inject CO_2 into a deep saline formation at a scale of 1 Mtpa.

Industrial sectors – steel, cement, chemicals, fertilizer, hydrogen, refining

In many industrial sectors, deep emissions reductions are typically not possible without CCS.

- Shell Quest - in November 2015 the Shell Quest CCS project in Canada became the first CCS project to reduce emissions from oil sands processing.
- Emirates Steel Industries (ESI) - A key large-scale CCS project development was the launch on November 2016 of the Abu Dhabi CCS Project, Phase 1 being the ESI CCS Project. This project represents the world's first application of CCS to iron and steel production. It involves the capture of approximately 0.8 Mtpa of CO_2 from the direct reduced iron (DRI) process used at the ESI plant in Abu Dhabi and its use for EOR.
- Tomakomai CCS Demonstration Project - Japan has embarked on an active program of pilot and demonstration CCS projects. The most notable development in 2016 was the commencement of CO_2 injection at the Tomakomai CCS Demonstration Project. The capture system (using emissions from a hydrogen production facility at Tomakomai port) is processing CO_2 at a rate of at least 0.1 Mtpa; this CO_2 is then injected into near-shore deep geologic formations.
- Lake Charles Methanol - The largest industrial facility with CCS in advanced planning. The facility would convert petroleum coke sourced from oil refineries in the Gulf Coast region into synthetic gas (syngas). The syngas would then be processed to produce methanol (the project's primary product), hydrogen gas, sulfuric acid and CO_2. Lake Charles would be designed to capture over 4 Mtpa of CO_2. Overall, the project would capture 77% of total CO_2

produced. The captured CO_2 will most likely be transported 225 km to oil fields in the Houston area for EOR.

- Other projects - Alberta Carbon Trunk Line, Alberta, Canada; Enid Fertilizer, Oklahoma, US; Illinois Industrial CCS Project, Illinois, US; Coffeyville Gasification Plant, Kansas, US; Great Plains Synfuel and Weyburn Midale project, North Dakota/Saskatchewan, US/Canada; Air Products Steam Methane Reformer, Texas, US.

Natural gas processing

Removal of excess CO_2 content in natural gas streams is a candidate for early CCS deployment, as the CO_2 must be separated from the gas before it can be sold. Natural Gas quality requirements for 'sales' gas requires that its composition is almost entirely methane, which is achieved by extracting impurities from the natural gas through a series of processes. Raw natural gas contains – in addition to CH_4 - a range of other substances including water, carbon dioxide, nitrogen, sulphur compounds, and other higher chain hydrocarbon gases such as ethane, propane, butane (which constitute liquefied petroleum gas or LPG).

Natural gas processing plants use a range of different processes to remove these various impurities and produce pipeline quality dry natural gas. Some of these substances, such as hydrocarbon liquids, LPG and sulphur, have commercial value and can be sold separately. Others, such as water and nitrogen, usually have no value and are re-injected into the gas reservoir or released. CO_2, as well, can be stored rather than being vented into the atmosphere, as was done in number of projects around the world:

- Val Verde Natural Gas Plants - The first of these projects started in 1972, using a waste stream of by-product CO_2 from several natural gas processing facilities in the Val Verde area of southern Texas. Instead of being vented, the CO_2 that had already been separated from the natural gas stream in the Val Verde gas plants was compressed and transported through the first large scale, long distance CO_2 pipeline to an oil field several hundred kilometers away elsewhere in Texas. The CO_2 was then injected into the SACROC (Scurry Area Canyon Reef Operators Committee) Unit of the KellySnyder Field in Scurry County, West Texas. The output of the Val Verde plants is dependent upon the quality of the natural gas being treated. The CO_2 content of the inlet gas stream can vary between 25-50 per cent in many cases. The total capture capacity of the Val Verde plants is around 1.3 Mtpa. The increased production of the SACROC petroleum reservoirs in response to the injected CO_2 convinced several other major oil companies of the viability of this technique. In any given reservoir, the amount of CO_2 co-produced with oil will increase with time; but the recycling systems employed at sites ensure that the vast majority of this CO_2 is reinjected into the reservoir in a closed loop system. EOR sites are designed to optimize oil recovery and minimize CO_2 purchases, so the storage resulting from EOR is often termed associated or incidental.

- Shute Creek Gas Processing Facility - The Shute Creek, Wyoming, US, gas treating facility began operation in 1986 and an expansion in plant capacity was completed in 2010. The plant processes gas from production units in the nearby LaBarge gas field. The Shute Creek plant handles among the lowest hydrocarbon content natural gas commercially produced in the world. The raw gas entering Shute Creek contains about 65 per cent CO_2 and 20 per cent methane, as well as nitrogen, hydrogen sulphide, helium and other gases. Carbon dioxide production capacity is 7 Mtpa. The separated CO_2 is transported from the Shute Creek facility under sales contract via the ExxonMobil, Chevron and Anardarko Petroleum pipeline systems to oil fields in Wyoming and Colorado for use in EOR. Pipeline distance from Shute Creek to the larger volume customers of Salt Creek and Rangely is approximately 460 km and 285 km, respectively.
- Sleipner CO_2 Storage Project - The Sleipner area gas development is located in the Central North Sea, near the border between the UK and Norway and approximately 240 km west-southwest of Stavanger, Norway. The CO_2 content of the gas stream from the Sleipner West field within the development is in the range of 4-9 per cent, which must be reduced to meet customer requirements. Since 1991, the Norwegian government has implemented a CO_2 tax on a number of sectors, including offshore petroleum production. The need to process Sleipner West gas to meet market specifications, the CO_2 tax, and a commitment to sustainable energy production, led the Sleipner project operator, Statoil, to capture and store CO_2 in a deep saline aquifer, which makes this project to be the first project where CO_2 storage was done for mitigation. Since production began in 1996, the gas has been processed at an offshore platform, and the captured CO_2 compressed and injected from another offshore platform into a sandstone reservoir 250 meters thick at a depth of 800-1,100 meters below sea level. The seal to the reservoir is provided by a 700 meter thick gas-tight caprock. Approximately 1 Mtpa of CO_2 is injected per year, with a total of 17 Mt throughout the 20 years of activity. This development was the world’s first demonstration of

CCS technology for a deep saline storage reservoir and the first large-scale CCS project to become operational in Europe.

- Snøhvit CO_2 Storage Project - Snøhvit is a liquefied natural gas (LNG) development in the Barents Sea offshore northern Norway. Snøhvit Area gas contains 5-8 per cent CO_2 by volume, which will solidify into dry ice under the pressure and temperature conditions of liquefying natural gas. It must therefore be removed before the gas is processed into LNG. LNG-separated CO_2 is typically released to the atmosphere; however, the Norwegian State mandated CCS as a condition of the license to operate for Snøhvit. The unprocessed raw natural gas stream is transported 143 km to shore and into an LNG plant located at Melkøya, Norway. The CO_2 removal process at the LNG plant is designed to capture 0.7 Mtpa of CO_2 when the facility is at full capacity. A separate pipeline then transports the CO_2 from the LNG plant back to the Snohvit field offshore where it is injected into a geological storage reservoir. Injection of CO_2 started in April 2008.
- Century Plant - The Century Plant natural gas processing facility in Texas, US, has the largest CO_2 separation capacity in the world. Located in Pescos County, Century Plant processes high CO_2-content (more than 60 per cent) gas from various fields in West Texas. The CO_2 is then compressed and transported for use in Permian Basin EOR operations elsewhere in Texas. Construction of the Century Plant facility was completed in two stages – the first stage was on-stream in late 2010, the second became operational in late 2012. Full CO_2 capture capacity is 8.4 Mtpa.
- Lost Cabin Gas Plant - The Lost Cabin Gas Plant is a natural gas processing facility in Wyoming, US. It began operation in 1995 and had a number of major expansions in 1998/1999 and 2002. The feed gas contains a high percentage of CO_2 at around 20 per cent. For much of the plant's history, the captured CO_2 was vented to the atmosphere. However, in 2010 Denbury and ConocoPhillips (owner and operator of the Lost Cabin Gas Plant) entered into an agreement for Denbury to purchase approximately 0.9 Mtpa of CO_2. Denbury would also build compression facilities adjacent to the gas plant and a new 374 km pipeline from the plant to an EOR injection site at the Bell Creek oil field in Montana, US (the Greencore CO_2 pipeline). ConocoPhillips began CO_2 deliveries in March 2013 and CO_2 injection began in May 2013.

- Petrobras Lula Oil Field CCS Project - Petrobras Lula Oil Field CCS Project is located approximately 300 km off the coast of Rio de Janeiro, Brazil. Lula was discovered in 2006 and is one of the largest oil field discoveries in Brazil. The hydrocarbon reservoirs are located in waters that can exceed 2,000 meters in depth. The reservoirs range in depth from 5,000 to 7,000 meters below sea level, under a salt layer that is more than 2,000 meters thick in places. The natural gas stream associated with oil production at Lula also contains CO_2. Application of EOR methods (including CO_2 injection) was considered from the early planning stages of field development. All production and processing is done at a floating facility on the ocean surface above the oil and gas fields. Large-scale production began in June 2013. The produced oil is offloaded into tankers and transported to shore. Gas processing units onboard the floating facility are designed to separate the CO_2 from the natural gas stream. Once separated, the gas output is transported to an onshore facility by pipeline. The CO_2 is compressed and re-injected into the producing oil and gas reservoir. The ultra-deep waters make the Lula field a pioneer in CO_2-EOR development, with the deepest CO_2 injection well in operation. Approximately 0.7 Mtpa of CO_2 can be re-injected into the Lula field.
- Uthmaniyah CO_2 EOR Demonstration Project - The Uthmaniyah CO_2-EOR Demonstration Project is located in a small area at the Uthmaniyah production unit, which forms part of the giant Ghawar field in Saudi Arabia (the largest oil field on Earth). The project compresses and dehydrates CO_2 from the Hawiyah NGL (natural gas liquids) Recovery Plant, then transports the CO_2 stream 85 km to the injection site within the Uthmaniyah production unit. Around 0.8 Mtpa will be injected for three to five years from commencement of the project, which was in July 2015. The Kingdom of Saudi Arabia has abundant conventional hydrocarbon reserves and EOR is not likely to be required at production scale for decades to come. However, the Uthmaniyah Demonstration Project has been developed to gain experience with this technique, including determining incremental oil recovery.
- Gorgon Project - The offshore Western Australian Gorgon natural gas production project with the first LNG delivery made in 2016 is the largest in the world to inject CO_2 into a deep saline formation (being capable of injecting up to 4 Mtpa of CO_2). The Project plans to inject between 3.4 and 4 million tonnes of CO_2 each year. This will reduce greenhouse gas emissions from the Gorgon Project by approximately 40 percent.

- Salah, Algeria - This gas processing plant began stripping and storing carbon dioxide from natural gas in 2004. Capture was suspended in 2011 as there had been concerns about possible leakage. At that point, 3.5 million tonnes had been stored in a saline aquifer. Monitoring continues at the site and future storage is under review.
- Jilin CCS facility - Jilin CCUS is located in northeastern China and is capturing CO_2 from a natural gas processing plant at the Changling gas field and transporting it by pipeline to onshore injections sites, for EOR. In August 2018, the facility announce that it has reached a storage capacity of 0.6 Mtpa of CO_2 and by that become the world's 18th large-scale CCS facility. Over the past year, China has shown a massive resolve to deploy CCS technology and there are now more than 20 projects in various stages of development. CCS is now part of long term, five-year strategic plans across China and acceleration has been aided by the roll-out of an emissions trading scheme, with a carbon price about to be introduced.

A summary of the above projects is provided in Appendix A.

The ability to scale up the existing operations of CCS relies on several critical factors. Table 2-3 lists the risks, potential impacts, and management approaches for dealing with them.

Table 2-3 > Summary of key risks, environmental impacts, and management approaches

Environmental Risk	Impacts	Management Approaches
Leakage of CO_2 into the atmosphere	Ineffectiveness of CCS	Effective site selection and monitoring Remediation of leakage pathways
Accumulation of elevated CO_2 concentrations in ecosystems	Damage to CO_2-sensitive habitats	Effective site selection and monitoring Remediation of leakage pathways & ecosystem cleanup
Accumulation of elevated CO_2 concentrations where humans can be exposed	Chronic or acute health concerns from CO_2 exposure	Effective site selection and monitoring Administrative controls to restrict access Remediation of leakage pathways
Leakage of CO_2 to groundwater	Acidification of groundwater and potential dissolution of toxic minerals	Effective site selection and monitoring Administrative controls to restrict groundwater use Remediation of leakage pathways & groundwater cleanup
Leakage of hydrocarbons to groundwater	Contamination of groundwater with organic compounds	Effective site selection and monitoring Administrative controls to restrict groundwater use Remediation of leakage pathways & groundwater cleanup
Displacement of saline brine into drinking water aquifers or surface water	Contamination of groundwater or surface water with dissolved salts	Effective site selection and monitoring Administrative controls to restrict groundwater use Remediation of leakage pathways and groundwater cleanup
Induced seismicity	Potentially felt ground motion and structural damage	Effective site selection and monitoring Regulatory limits on pressure buildup and consequent induced seismicity

(Source: de Coninck & Benson, 2014)

2.5 CO_2 Utilization

Utilizing CO_2 has received increasing attention in recent years, notably as a potential driver to develop CCS. The allure of CO_2 utilization is straightforward: instead of paying to dispose of CO_2 as a waste, firms that generate large amounts of CO_2 could be paid to deliver it as a commodity to willing buyers, while at the same time avoiding releasing emissions to the atmosphere and assuming associated penalties. If viable, CO_2 utilization could thereby shift the focus of the CCS discourse from the disposal of an inconvenient by-product or waste towards the production and use of a commodity.

However, not all options for CO_2 would actually help mitigate climate change. Understanding the emission reductions that arise from different CO_2 utilization options can often be complex and not all CO_2 utilization is equally beneficial from a climate perspective.

Millions of tonnes (Mt) of CO_2 are used in industry each year. The largest single source of this is EOR, where CO_2 is injected into oil reservoirs to increase mobility of oil and reservoir recovery, with some 70 Mt CO_2 used annually, although two-thirds of the quantities used are actually from natural CO_2 sources (IEA, 2016a). In time, this could be replaced with CO_2 captured from power and industrial facilities and, with appropriate site characterization and monitoring, could provide a permanent storage solution.

Other current large-scale uses (in millions of tonnes per annum (Mtpa)) include urea yield boosting, carbonated drinks, water treatment and pharmaceutical processes. However, these uses are relatively limited when considered from the perspective of tackling climate change: for example, the global beverage industry uses around 8 Mt CO_2 each year, which is approximately 0.5% of the CO_2 that would need to be captured and stored in the IEA 2DS by 2030 (IEA, 2016a). Most of these alternative large-scale uses also do not offer a permanent storage solution. Emerging CO_2 utilization opportunities such as mineral carbonation and CO_2 concrete curing have the potential to provide long-term storage in building materials, but again the potential contribution of these measures to climate change is likely to be limited as demand for these products become saturated (IEA, 2014). The proposed conversion of CO_2 to liquid fuels could potentially displace fossil fuel use (thereby reducing emissions) but requires extensive energy use and would not deliver the same net climate benefit as geological storage because in such conversion the CO_2 is ultimately re-released.

There are many classifications that can be made about the use or valuation of large-scale CO_2 which include three categories (Llamas et al., 2016):

1. **Direct or technology use** - use of CO_2 with different technologies and market applications, including:
    - **EOR** - Technology that injects CO_2 into a reservoir that contains hydrocarbons for the purpose of enhancing the pressure in the oil field and allow faster oil recovery from depleted oil fields. The CO_2 is produced along with the oil and then recovered and re-injected to recover more oil. When the maximum amount of oil is recovered from the reservoir, the CO_2 is then injected into the underground geologic zone that formerly contained the oil and the well is shut-in, permanently sequestering the CO_2. In the first commercial project of EOR in 1972 (SACROC project in Texas), the source of the CO_2 was a gas plant, where the CO_2 was eliminated in the production of ammonia. Two techniques are largely used for EOR: **Miscible water-alternating-gas (WAG) process,** where gas (usually natural gas or CO_2) and water alternately injected to form one phase with the oil to increase its viscosity and improve the sweep efficiency; **Cyclic gas injection,** usually CO_2 (either natural or industrial by product). The CO_2 is injected under pressure between oil wells to free the stranded oil. Carbon dioxide is a superior agent in recovering stranded oil as it naturally reduces the surface tension that traps the liquid oil in the reservoir. The CO_2 is produced with the oil but is easily separated from the crude oil because it reverts back to its gaseous state when the pressure is removed.
    - **Fire suppression** - Carbon dioxide is denser than air and it can blanket a fire, because of its heaviness. Some fire extinguishers use CO_2 which prevents oxygen from getting to the fire and depress it.
    - **Supercritical CO_2** - Supercritical CO_2 is a fluid state where CO_2 is held at or above its critical temperature and pressure, and it behaves as a supercritical fluid (expanding to fill its container like a gas but with a density like that of a liquid). This state emphasizes the capacity of CO_2 to dissolve chemicals and natural substances similar to different organic solvents. The most mature application at the industrial level is the removal of caffeine (coffee or tea) and also in the extraction of hops or cocoa fat. Another popular application is in dry cleaning, where supercritical CO_2 is used to

remove stains from fabrics and garments without causing discoloration or shrinkage and without associated smells. Supercritical CO_2 extraction is also used by producers of flavors and fragrances to separate and purify volatile flavor and fragrance concentrates.

- **Food and beverages** - In transport of food, liquid or solid CO_2 is used for quick freezing, surface freezing, chilling and refrigeration. CO_2 is also used to carbonate soft drinks, beers and wine and to prevent fungal and bacterial growth, since it has an inhibitory effect on bacterial growth, especially those that cause discoloration and odors**.**
- **Water treatment** - CO_2 technology is widely introduced in treatments such as sewage water, industrial water or drinking water remineralization. These processes used the chemical ability of CO_2 to change the pH of water and to increase water hardness (when combined with lime or calcium hydroxide).
- **Carbonate mineralization** - Another technological use of CO_2 is the accelerated carbonation of alkaline waste. The chemical reaction of alkaline with CO_2 produces minerals, such as calcium carbonate and magnesium carbonate, which are highly stable and can be used in construction and as filler materials in paper and plastic products, without concern that the CO_2 they contain will be released into the atmosphere.

2. **Improved biological use (Biological utilization)** - This technology, also known as biomimetic transformation, imitates the nature's process of photosynthesis and uses CO_2 as food for plant growth. There are two main ways in the biological utilization process: **greenhouses carbonic fertilization** and **growth of microalgae**. In the first process yields of plant products grown in greenhouses can increase by 20% by enriching the air inside the greenhouse with CO_2 (the target level for enrichment is typically a CO_2 concentration of 800 ppm). The carbonic fertilization allows for early crop production along with a greater amount of product with better quality. The second process seeks to exploit the advantage of microalgae as a microorganism with a high production rate (some species are able to duplicate their biomass in 24 hours, about 30 to 60 times the rate of land-based plants). On top of this, some species of seaweed are super stable and don't break down easily, meaning they have a high potential for long-term carbon storage. In the middle of the last century, the investigation on bio-fixation of CO_2 by microalgae focused on the possibility of obtaining biofuels from microalgae: mainly methane (CH_4) and H_2, but after the oil crisis in the 1970s the biodiesel was also considered, which could reduce the need for fossil fuels. However, none of the projects have demonstrated the feasibility of the

concept at a pre-industrial level. The efforts focus on nutritional purposes (for humans) and animal feed (especially aquaculture). Other sectors, such as cosmetics, effluent treatment and bioenergy, have shown interest, incorporating microalgae into commercial products, for example, Venus Shell Systems[6], an Australian company that produce marine biomass used in biomaterials, cosmetics, nutraceuticals and pharmaceuticals, has pioneered a project that produces seaweed that captures CO_2 produced by an ethanol plant located next to this facility. Algenol[7], a US company, is commercializing a technology that creates ethanol and other fuels from algae. Their process allows algae to convert sunlight, seawater and waste CO_2 into sugar much faster than through natural photosynthesis. Through fermentation, the sugar is converted into ethanol and biomass, which is further refined into green gasoline, jet fuel and diesel. Currently, 95% of the production of microalgae is based on open systems (raceways or circular open ponds). These systems have a low rate of CO_2 fixation and it is estimated to be around 20-50% of the injected gas is effectively set by microalgae (Llamas et al., 2016).

3. **Chemical use** - Carbon dioxide gas is used, by **artificial photosynthesis** and **chemical conversion** to high added value products and fuels, such as: urea (used as a fertilizer, in automobile systems and medicine), MeOH, inorganic and organic carbonates, polyurethanes and sodium salicylate. Carbon dioxide is combined with epoxides to create plastics and polymers.

Significant innovation and technical progress are being achieved across a number of utilization technologies. By the end of 2014 a European company (ETOGAS[8]) presented their 'Power to Gas' technology, which converts CO_2 and H_2 to CH_4 (syngas) through electrolysis processes. Another German company (Covestro[9]) develops a technical process to produce CO_2-based polymers production on a large scale. In this process, CO_2 acts as a substitute for the petroleum production of plastics. The polymers are used in many everyday applications, they can be used for the insulation of buildings, in the automotive industry, upholstered furniture and mattress manufacturing. Another trial in that direction is made by Newlight Technologies[10] in their production sites in California where carbon emissions from farms, landfills and energy facilities is captured and combined with oxygen into a substance called Aircarbon, which is, according to the company, a

---

[6] Venus Shell Systems - https://www.venusshellsystems.com.au/about-us/
[7] Algenol - http://algenol.com/
[8] Hitachi Zosen Inova Etogas - http://www.hz-inova.com/cms/en/home?page_id=4896
[9] Covestro - https://www.covestro.com/en
[10] Newlight Technologies - https://www.newlight.com/

cost-effective way of making plastic. A Spanish company (Iberdrola[11]) developed an application for power plants which uses the flue gases from Combined Cycle Power Plants (CCPP) in a direct way to control the PH in the cooling water systems. That company also seeks to demonstrate the viability of using CO_2 from combustion gases to control macro-fouling (fouling caused by larger organisms) in a thermal power plant (Castellon CCPP), cooled by sea water. In this process CO_2 is used as a substitute for chlorine-based chemicals. First estimates indicate that a 400 Megawatt (MW) CCPP may be necessary to use annually up to 50,000 tCO_2. A building materials company from California (Blue Planet[12]) is sequestering waste CO_2 from California's largest power plant (as well as cement manufacturers in Mexico and Canada, steel mills in Mexico, aluminum plants in Canada and coal-fired power plants in Wyoming) into manmade limestone. While bubbling waste gases through seawater it removes about 90% of the CO_2 and combines it with minerals in the water, resulting in the creation of limestone that is composed of about 50% waste CO_2. An Australian company (Mineral Carbonation[13]), makes similar efforts. Another US company (Solidia[14]) sequesters carbon in building materials by curing concrete with CO_2, instead of water, to produce stronger and more stable concrete while reducing water and energy use.

The current and future role of CO_2 utilization should be evaluated while considering the following aspects (IEA, 2016a):

- **Emissions reductions:** The impact of CO_2 usage depends primarily on whether it achieves emission reductions. Analyzing this issue requires a good understanding of the utilized CO_2. Alternatively, does the use displace more carbon-intensive fuel consumption? This requires an understanding of both the used CO_2 and of the displaced consumption.
- **Financial contribution:** Utilization can also have an indirect climate change mitigation benefit. For example, it can create a profitable business opportunity which acts to stimulate increased investment, which in turn leads to innovation in CCS technology, and the revue can help cover the cost of capture operations.
- **Scalability of use:** A question needs to be raised: *Can the use be scaled up to drive the building and operation of large-scale capture facilities?* Large point sources will potentially capture several million tonnes of CO_2 annually, therefore, sufficient demand is critical. Opportunities for

---

[11] Iberdrola - https://www.iberdrola.com/home
[12] Blue Planet - http://www.blueplanet-ltd.com/
[13] Mineral Carbonation International - http://mineralcarbonation.com/
[14] Solidia Technologies - http://solidiatech.com/

CO_2 utilization are likely to be limited to niche applications with relatively small-scale CO_2 requirements (with the exception of EOR). These may have value at a local or industrial level, but are not considered an alternative to large-scale geological storage of CO_2. Beyond EOR, the contribution of CO_2 utilization to emissions reduction efforts is likely to be limited in the absence of major technical breakthroughs. It should therefore not be positioned as an alternative to geological storage of CO_2.

3 MATURE CCS TECHNOLOGIES

Low-carbon energy generation technologies – especially those that require the application of CCS – are at varying stages of technological development and often straddle one or more development stages as new designs and configurations are developed. In this chapter we compare various such CCS technologies for maturation, efficiency and cost.

3.1 CCS technologies comparison

3.1.1 Maturation

> ***Mature technology** is defined as a technology that is being used at an industrial scale in at least one industrial facility. It is a technology that meets a certain Technology Readiness Level (TRL)[15] as used by the U.S. Department of Energy (Folger, 2013) and other organizations. All of the technologies that are described as mature in this chapter are either being used on an industrial scale for several years, in at least two industrial facilities.*

CO_2 Capture

Currently there are only few mature carbon-capture technologies. The most mature technologies involve CO_2 absorption as part of separation techniques:

- **For post-combustion** - the absorbers of choice are amines (see Table 3-1).
- **For pre-combustion -** the absorbers of choice are dimethyl-ethers of polyethylene glycol or refrigerated MeOH. Membranes are also used on an industrial scale for CO_2/CH_4 gas separation (de Coninck & Benson, 2014) (see Table 3-2).
- **For oxy-combustion** - cryogenic oxygen separation is the mature technology (see Table 3-3).

Only for these technologies there are years of industrial experience.

Post-combustion CO_2 absorption by ammonia is an almost mature technology, with a few pilot projects that have been running for up to a decade (Folger, 2013), but with no industrial scale projects yet (a few planned industrial-scale projects were canceled in the last few years).

The rest of the technologies are, at best, at pilot stages, and most are at bench and development stages. This means that they will probably not be industrially available until 2025.

---

[15] Technology Readiness Level is a metric used for describing technology maturity. It is a measure used by many U.S. government agencies to assess maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating that technology into a system or subsystem.

Table 3-1 > Comparison between post-combustion carbon-capture technologies

	Description	Maturation	Efficiency	Cost	Advantages	Challenges
Absorption	CO_2 from the gas stream is dissolved in a solvent fluid, later is removed by pressure or temperature change. The solvent is reused. The most common absorbers are amines that react chemically with the CO_2.	Mature, decades of experience, demonstrated at industrial scale (8 Mt CO_2/year).	50-100%	High Post Comb. Cost	Mature. Very efficient. Fast kinetics for low partial CO_2 pressure (post combustion CC). Suitable and industrially applied in post and pre-combustion CC.	Still very expensive. High energy consumption. Moderate environmental impact. Aqueous solvents use a lot of water. Operation is complex. Long construction time.
Adsorption	CO_2 from the gas stream is adsorbed onto a solid, later is removed from the solid by pressure or temperature change. The solid is reused.	Bench and small-scale pilot testing.	No data	No data	Lower energy use for solid regeneration. Fast kinetics for low partial CO_2 pressure (post combustion CC).	Adsorption capacity. Heat management is difficult in solid systems.
Cryogenic	The gas stream is cooled, CO_2 turns into solid and is separated from the gas.	Limited deployment of industrial scale CO_2/CH_4 separation. Bench and small-scale pilot testing for flue gas separation.	High efficiency	No data	No need for solvents or sorbents. Lower energy requirements.	It is still challenging to separate the solid CO_2 from the gas. High energy consumption, and therefor high cost.
Membranes	CO_2 from a pressurized mixed gas stream is preferentially transported through a membrane.	Limited deployment of industrial scale CO_2 and H_2/CH_4	Low efficiency	Low cost	Operation is simple. Fast construction time. Low to moderate energy consumption.	Low efficiency. Not suitable for low pressure processes (post-combustion CC).

	Description	Maturation	Efficiency	Cost	Advantages	Challenges
		separation (7 Mt/year).			Low environmental impact. No chemicals needed.	Either low recovery rate and high purity, or vice versa. Poor economy of scale. Might require multiple stages and recycle streams.
Mineralization	CO_2 reacts with calcium or magnesium-bearing rocks to form magnesite or calcite.	Under development.	No data	No data	CO_2 is turned into a stable solid substrate that can be used as a building material or dumped.	Low rate of mineralization. Need for a huge mass of calcium or magnesium-bearing rocks. High energy consumption. Environmental impacts from mining.

(Sources: Boot-Handford et al., 2014; Chapman et al., 2013; de Coninck & Benson, 2014; Folger, 2013; Muratori et al., 2017a; Rubin et al., 2015; Shimekit & Mukhtar, 2012)

Table 3-2 > Comparison between pre-combustion carbon-capture technologies

	Description	Maturation	Efficiency	Cost	Advantages	Challenges
Absorption (Selexol^{TM}, Rectisol®)	CO_2 from the gas stream is dissolved (physical reaction) in a solvent fluid (dimethyl-ethers of polyethylene glycol or refrigerated MeOH). Later, CO_2 is removed from the solvent by pressure or temperature change. The solvent is reused.	No commercial CCS projects use this method. However, it is being used for almost 20 years for other industrial processes, for removing pollutants as SO_2 and NO_x, and for separating CO_2 from H_2 during coal/petcoke gasification for fertilizer/ natural gas production.	50-90%	Relatively low	Mature. Very efficient. Fast kinetics for low partial CO_2 pressure (post combustion CC). Suitable and industrially applied in post and pre-combustion CC.	Moderate environmental impact. Aqueous solvents use a lot of water. Operation is complex. Long construction time.
Membranes	CO_2 from a pressurized mixed gas stream is preferentially transported through a membrane. Or, from a mix of CO_2+H_2, H_2 is preferentially transported through a membrane and the CO_2 is left behind.	Limited deployment of industrial scale CO_2 and H_2/CH_4 separation (7 Mt/year).	Low efficiency	Low cost	Operation is simple. Fast construction time. Low to moderate energy consumption. Low environmental impact. No chemicals needed. Suitable especially for gas mixtures with high CO_2 concentration (pre-combustion CC).	Low efficiency. Not suitable for low pressure processes (post-combustion CC). Either low recovery rate and high purity, or vice versa. Poor economy of scale. Might require multiple stages and recycle streams. Some H_2 is lost with the captured CO_2.

(Sources: Boot-Handford et al., 2014; de Coninck & Benson, 2014; Folger, 2013; Im et al., 2015; Rubin et al., 2015; Shimekit & Mukhtar, 2012)

Table 3-3 > Comparison between oxy-combustion carbon-capture technologies

	Description	Maturation	Efficiency	Cost	Advantages	Challenges
Cryogenic oxygen separation	Here, the separation is for O_2 before combustion, and the result is flue gas that is mostly CO_2. Air is cooled until oxygen is turned into liquid, and separated from the rest of the gases. The combustion process is fed with 95% pure oxygen, resulting in CO_2 and water vapor that is easily removed.	The Cryogenic oxygen separation is a mature process, used in many industrial processes. However, due to the high energy penalty and high cost, still there are no industrial scale plants. Advanced oxygen separation technologies are being developed.	95-99%	High cost due to high energy penalty for cryogenic oxygen separation. 2013 data shows comparative prices to those of post-combustion technologies (Folger, 2013).	Mature. No need for CO_2 capture module/technology. Operation is simple. Low environmental impact (besides the high energy demand). No chemicals needed.	The energy penalty is high, and comparable to that of post-combustion amine CC. Thus, the cost of this technology is very high. Remove pollutants such as SO_2 and NO_x.

(Sources: Boot-Handford et al., 2014; Folger, 2013; Shimekit & Mukhtar, 2012)

CO_2 Transport

CO_2 Pipeline transport is a mature, relatively cheap and well-regulated technology, with several decades of experience. Most of the experience is from U.S. EOR projects that flood the reservoirs with supercritical CO_2 (CO_2-EOR) to enhance recovery of resource from hydrocarbon reservoirs. There is an interest in developing CO_2 pipeline networks in Europe, Canada and Australia. This in order to enable transport of CO_2 from production or processing sites - where it is captured - to onshore and even offshore storage sites. The latest development in the field is an offshore underwater pipeline in the Norwegian Snøhvit project in the Barnets Sea (IEA, 2016a; Noothout et al., 2013).

Ship transport is a mature technology. It is more cost-effective for distances longer than 2400 km, compared to pipelines transport. It allows the flexible transport of CO_2 from coastal regions to multiple locations. It can facilitate the growth of multiple coastal CO_2 production hubs that could later be connected to a pipeline network. However, no CO_2 transporting ships network has been established yet (IEA, 2016a).

Storage / Utilization

Storage - plenty of research was conducted since 2005, to study the safest ways to store CO_2 underground. Current evidence shows that deep saline formations are the largest and most likely geological storage option. There is high degree of confidence in the adequacy of saline formations as permanent storage reservoirs. It is estimated that the storage capacity of the global deep saline formations ranges between 1,000-10,000 Gt of CO_2. Other reservoirs categories include depleted oil and gas fields, un-minable coal seams, basalts, shales, salt caverns and abandoned mines. The overall estimated storage capacity for these other reservoirs is 2,000-11,000 Gt of CO_2 and can accommodate 10-15% of the annual anthropogenic CO_2 emissions, for 300-1500 years (with annual anthropogenic CO_2 emissions of 40 Gt). There are decades of experience with EOR that pumps CO_2 into underground formation, and more than 20 years of experience with designated CO_2 storage in deep saline formation for CO_2 mitigation (IEA, 2016a; IPCC, 2014).

Some CO_2 **utilization** technologies are mature. The most prominent is EOR that uses about 70 Mt CO_2 annually for decades. However, this technique requires continued separation and recycling of the CO_2 that is blended with the produced oil until production is terminated and CO_2 is stored permanently. Also, currently, this scale is not large enough to contribute significantly to affect our global CO_2 emissions rate.

Other mature technologies, such as urea production, carbonated drinks, water treatment, fire suppression, plant growth enhancement, supercritical CO_2, and pharmaceutical processes - are used at a more limited scale annually.

Newer technologies such as plastic production, fuel production, mineral carbonization for building materials production, and chemical use - are not yet used commercially and are not fully mature. These technologies have a potential for large-scale CO_2-utilization that can affect the global CO_2 emissions rate. Among these technologies, plastic and building material production can trap CO_2 for hundreds to thousands of years (and even more).

3.1.2 Efficiency

__Efficiency__ is defined as the percentage of CO_2 that is captured or used, and the percentage that is not released back to the atmosphere for at least many decades.

CO_2 Capture

CO_2 capture by amines absorbers has 50-100% efficiency, depending on the amine, facility design, and the specific method used. In contrast, membranes have low capture efficiency, which cryogenic oxygen separation has high efficiency (Folger, 2013) (see Tables 3-1, 3-2 and 3-3).

CO_2 Transport

CO_2 transport by pipeline and ships is highly efficient, with minimal CO_2 loss to the atmosphere (IEA, 2016a). It is believed that CO_2 loss is similar to that of natural gas loss from natural gas systems, which is smaller than 10% of the produced natural gas (Caulton et al., 2014; IEAGHG, 2004; Onyebuchi et al., 2018; Schneising et al., 2014).

Storage / Utilization

CO_2 **Storage** in deep saline formations has high efficiency. Experimental and model data show that carefully and properly chosen and maintained and monitored CO_2 injection sites can trap CO_2 permanently, for millions of years (IEA, 2016a; IPCC, 2005). Substantial CO_2 leakage can occur only through wells and faults. Even in these cases, the highest leak rate is 8% of the CO_2 injected per 100 years after injection stops. This rate can be reduced to less than 1% per 500 years by various mature and available remediation methods (Zahasky & Benson, 2016).

CO_2 **Utilization** in short-lived products (life span of up to a few years), such as urea production, carbonated drinks, water treatment, fire suppression, plant growth enhancement, supercritical CO_2, pharmaceutical processes, plastics (if they are quickly turned into waste and then to energy) - may be efficient in conversion to the product but the CO_2 that was incorporated into these products is released back to the atmosphere after a short period of time. Utilization into stable products, like mineral carbonization into building materials and long-lasting plastic, could be highly efficient.

3.1.3 Cost

The definitions below are provided to explain the terminology used in the cost analysis.

More details about the currencies conversions can be found in Appendix B.

Definitions:

CO_2e captured (ton/MW hour (MWh)) *- How many tons of CO_2e are captured per MWh produced.*

CO_2e avoided (ton/MWh) *- CCS power plant uses more energy (or more natural gas) to produce 1 MWh of electricity, because there is an energy penalty (15-24%) due to the energy used to capture the carbon and not to produce the electricity. Although 90% of the carbon may be captured per unit of energy produced, it takes a higher resource heating value to generate 1 MWh of electricity. Therefore, per MWh produced, the CCS power plant avoids only 88% of carbon emissions, compared to the conventional power plant.*

COE *- cost of electricity generation ($/MWh).*

COE_{ref} *- cost of electricity of a reference power plant without carbon capture.*

COE_{CC} *- cost of electricity with carbon capture.*

Cost of CO_2e abated [ILS_{16}[16]/tCO_2] *- when multiple strategies are used to reduce GHG emissions, we use the term cost of CO_2e abated (CO_2e abatement costs). Examples are GHG emissions reduction in power plants, in fuel production, changes in the fuel mix, improved efficiency etc.*

---

[16] ILS_{16} - Israeli Shekel, mid 2016 values. This is the currency we used compare between the different currencies from the different references.

Cost of CO_2e captured *is the price of capturing every ton of CO_2e. It represents the minimum CO_2e plant gate sales price that would incentivize carbon capture instead of a corresponding non-capture plant based on the same technology. It is not calculates for the whole CCS operations chain, only for CC (Rubin, 2012). For example, for an electric power plant the cost can be defined as:*

$$Cost\ of\ CO_2e\ Captured\ \left(\frac{ILS_{16}}{tCO_2e}\right) = \frac{(COE)_{cc} - (COE)_{ref}}{\left(\frac{tCO_2e}{MWh}\right)_{captured}} \tag{1}$$

Cost of CO_2e avoided *represents the minimum CO_2e emissions price that would, when applied on both the capture and non-capture plants, incentivize carbon capture instead of a defined reference plant without CCS (Rubin, 2012) (the carbon tax value or emission fee that will make the COE of a power plant with CCS equal to a power plant without CCS). CCS power plant uses more energy (or more natural gas) to produce 1 MWh of electricity, because some energy (15-24%) is used to capture the carbon and not to produce the electricity. Although 90% of the carbon is captured per BTU of natural gas, more BTUs (or carbon) are now used to create 1 MWh of electricity. Therefore, per MWh produced, the CCS power plant avoids only 88% of carbon emissions, compared to the conventional power plant. The cost of CO_2e avoided for a power plant defined as:*

$$Cost\ of\ CO_2e\ Avoided\ \left(\frac{ILS_{16}}{tCO_2}\right) = \frac{(COE)_{ccs} - (COE)_{ref}}{\left(\frac{tCO_2e}{MWh}\right)_{ref} - \left(\frac{tCO_2e}{MWh}\right)_{ccs}} \tag{2}$$

Figure 3-1 illustrates the difference between CO_2 captured and CO_2 avoided. The upper panel is life-cycle CO_2 emissions in NGCC power plant without CCS. The lower panel is life-cycle CO_2 emissions in NGCC power plant with CCS. Note that CCS in a power plant, cannot capture other CO_2 emissions in the life cycle of producing electricity (infrastructure, fuel production and transport, etc.). Moreover, CCS itself leads to further CO_2 emissions. Therefore, even a technology that captures 90% of the CO_2 emissions in a power plant, can only capture about 65% of the life cycle GHGs in a NGCC power plant (Cuéllar-Franca & Azapagic, 2015; Sathre et al., 2011).

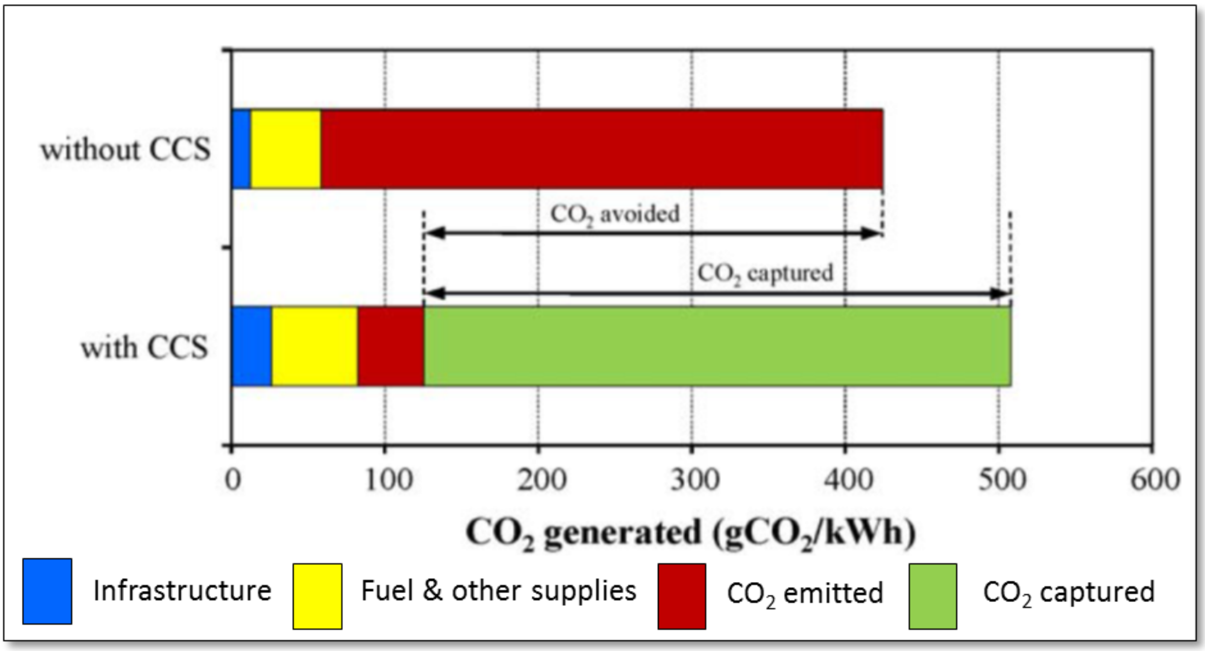


Figure 3-1 > A visualization of the difference between CO_2 captured and avoided (Adopted from singh et al. (2011))

CO_2 Capture

Mature CCS processes require a substantial amount of energy to operate: 10-100 times higher than other environmental control systems employed in power plants. Thus, adding CCS to a power plant reduces the power plant's efficiency, as can be seen in Table 3-4.

- 60% of this energy penalty is attributed to thermal energy for amine solvent regeneration (post-combustion), or loss in water-gas shift reaction (pre-combustion), or electricity for oxygen production (oxy-combustion);
- 30% of this energy penalty is attributed to CO_2 compression; and
- 10% of this energy penalty is attributed to pumps, fans, etc. (Folger, 2013).

Also, the mature technologies require extensive facilities, in amine absorbers there is a substantial loss of amines over time, and a lot of water is being used.

All these factors together, bring the capital cost of a **post-combustion** CCS natural power plant to cost as twice as much a conventional power plant, and the cost of electricity to increase by 40-120% (see Table 3-4).

In **pre-combustion** CO_2 capture, as of 2015, there were more than 110 commercial facilities that use

Selexol technology (Im et al., 2015), and many others that use Rectisol technology[17]. The wide use of these technologies (mainly for natural gas processing) helped to lower their cost. However, power generation cost in a coal IGCC power plant with Selexol CCS is still 30% higher than without.

Nonetheless, CO_2 capture cost with the Selexol technology, is only ~21 ILS_{16}/tCO_2e (~5.2 USD_{13}/tCO_2e) (Im et al., 2015). This is 14-18 times cheaper compared to post-combustion amine absorption technologies (280-570 ILS_{16}/tCO_2e, see Table 3-4). The Rectisol technology has higher capital cost and lower operating cost when compared to Selexol. Studies showed that In the long run, either Rectisol or Selexol were cheaper according to different case studies (Arienti et al., 2008).

The USA Congressional Research Service (CRS) report (Folger, 2013), gave a much wider range for pre-combustion CO_2 capture cost for industrial processes: 22-313 ILS_{16}/tCO_2e (5-70 USD_{07}/tCO_2e) for H_2\ammonia production or natural gas processing plant; and 134-648 ILS_{16}/tCO_2e (30-145 USD_{07}/tCO_2e) for all other industrial processes.

On average, 70-90% of the CCS cost is from the capture stage (Chapman et al., 2013; Folger, 2013). The variation depends on the capture technology, the nature of the facility (type of industrial process or power plant), and also on the transport and storage parameters (transport distance, onshore or offshore, EOR or deep saline formation).

Another study (Rubin et al., 2015), calculated that pre-combustion CO_2 capture cost in IGCC coal power plants using physical solvent scrubbing (similar to the Selexol and Rectisol technologies), can be as low as 135 ILS_{16}/tCO_2e (34 USD_{13}/tCO_2e). This is 6-7 times more expensive than carbon capture in industrial facilities (Im et al., 2015), but still 2-3 times cheaper than post-combustion (Rubin et al., 2015).

---

[17] RECTISOL® - https://www.the-linde-group.com/en/index.html

Table 3-4 > Post-combustion CCS in Natural Gas Combined Cycle (NGCC) power plants[18]

Reference	**IEA** (Finkenrath, 2011)	**UK CCS Task Force** (Chapman et al., 2013)	**CRS** (Folger, 2013)	**Rubin et al. (2015)**	**Muratori et al.** (2017)[19]
Ref. NGCC plant (no CCS)					
Net efficiency %	57%	54%	50%	51%	52%
Emission rate (tCO$_2$e/MWh)				0.36	
Capital cost (ILS$_{16}$/kW)	4099	3135		4164	4483
COE (ILS$_{16}$/MWh)	329	375	291	254	-
NGCC with carbon capture only					
Emission rate (tCO$_2$e/MWh)				0.04	
CO$_2$e reduction per MWh (%)				88%	
Net efficiency (%)	48%	45%*	43%	44%	42%
Relative decrease in net efficiency	15%	19%	16%	16%	24%
CO$_2$e captured (tCO$_2$e/MWh)	0.362*			0.36-0.39	
CO$_2$e avoided (ton/MWh)	0.315	0.315*	0.315*	0.31-0.33	
Capital cost (ILS$_{16}$/kW)	7323	7701*		8182	8967
Relative increase in capital cost	82%	145%*		96%	100%
COE (ILS$_{16}$/MWh)	436	589	393*	365	-
Relative increase in COE	33%	57%	35%*	45%	-
Cost of CO$_2$e captured (ILS$_{16}$/tCO$_2$e)	342	570*	282*	394	389
Cost of CO$_2$e avoided (ILS$_{16}$/tCO$_2$e)		678*	326*	345	141
Percentage of capture cost out of all CCS costs		70%*	80-90%		
NGCC with full CCS[20]					
COE (ILS$_{16}$/MWh)	-	821	411	250-484	-
Relative increase in COE	-	119%*	41%*	28-72%	-
Cost CO$_2$e avoided (ILS$_{16}$/tCO$_2$e)	-	1414* (offshore)	384* (onshore)	234-568 (onshore)	-

All data as appears in the articles, except when marked otherwise.
* Calculated from the article's data.

---

[18] The data with the original currencies is available in Appendix C.

[19] Calculated for the year 2020.

[20] The transportation and storage parameters are different in every article, therefor the results are more variable.

Transport and storage

Transport and storage make 10-30% of CCS cost, depending on the capture technology, and also on the transport and storage parameters: transport distance, onshore\offshore pipeline and storage. Table 3-5 summarizes the transport costs from four articles (Rubin et al., 2015).

Table 3-5 > Transport cost (ILS_{16}/tCO_2/250 km) at three different pipeline capacities

Pipeline location	Pipeline capacity 3 $MtCO_2$/yr	Pipeline capacity 10 $MtCO_2$/yr	Pipeline capacity 30 $MtCO_2$/yr
Onshore	17-43	9-15	5-9
Offshore	29-59	14-19	8-10

(Source: Rubin et al., 2015)

For onshore storage, the cost is between 4-71 ILS_{16}/tCO_2 (1-18 USD_{13}/tCO_2), based on five articles (Rubin et al., 2015). The lower end of the range is for cost of storage in depleted oil & gas fields (with at least part of the infrastructure already in place), and the high end of the range represents the cost of storage in deep saline formations.

These costs include known costs related to long term monitoring and maintenance of the storage facilities. This technology is new, with not a lot of years of experience. Especially when compared to the time-span these storage facilities are expected to store CO_2. Therefore, there is much uncertainty regarding the cost. We can compare it to a similar technology- hydraulic fracturing. There, public concerns have risen in the past decade regarding this technology. This led to modifications in operating procedures and higher costs (Rubin et al., 2015; Wolff, 2014).

If we take a case study in Israel, of transporting 3 $MtCO_2$/yr from central Israel to a deep saline-formation in the south (Northern Negev), for 150 km: using Rubin et al. (2015) numbers, the transport will cost 31-78 million ILS_{16} annually, and storing these 3 $MtCO_2$, will cost 107-214 million ILS_{16}. The total for transport and storage is 138-292 million ILS_{16}/3 $MtCO_2$/yr (35-74 million USD_{13}/3 $MtCO_2$/yr), or 46-97 ILS_{16}/tCO_2 (11.6-24.4 USD_{13}/tCO_2).

Collodi et al. (2017) used a cost of 43 ILS_{16}/tCO_2 (10 EUR_{14}/tCO_2) for transport and storage. Using these numbers, the cost for transporting and storing is 129 million ILS_{16}/3 $MtCO_2$/yr (30 million EUR_{14}/3 $MtCO_2$/yr).

Utilization

CO_2 utilization as a product offers lower overall costs for CCS, as selling CO_2 for production of goods is a source of income. Power plants selling CO_2 for EOR can reduce the COE from 250-484 to 191-445 ILS_{16}/MWh (63-122 to 48-112 USD_{13}/MWh). In other words, a COE that is lower by 10-30% compared to CCS without utilization, or - a COE that is 7-56% more expensive compared to a non-CCS power plant (Rubin et al., 2015).

A recent article showed that CCU in a MeOH plant, can be done without increasing the MeOH production cost and might even be profitable (Collodi et al., 2017). See Section 3.2 on methanol.

Future CCS cost

In many technologies, the cost of their implementation tends to decrease with time. This, due to economy of scale, improvement in production\implementation, more experience with the technology, etc. The same may happen with CCS technologies. For CCS in electricity production, the UK CCS task force proposed a roadmap for reducing the cost. This roadmap includes assignments needed to be performed in order to promote CCS cost reduction. Their roadmap suggests a CCS cost reduction of 40% within 15 years (2013-2028). In other words, lowering the COE from 589 to 353 (ILS_{16}/MWh) (Chapman et al., 2013). Even though this potential reduction is impressive, the cost after reduction is only slightly lower than the **average** COE in Table 3-4. This is because the UK task force COE cost was originally much higher than in the other sources (Finkenrath, 2011; Folger, 2013; Rubin et al., 2015).

We believe that it is probable that the CCS cost will be reduced as the technology matures and as more and more CCS projects are realized. However, not a lot of CCS projects are currently being built of planned. There are only a handful of CCS projects that are expected to be constructed in the next 5 years, and only 16 that are in the planning stage. Therefore, the learning curve in the field is not expected to rise quickly, and the cost is not expected to be reduced considerably in the next 5-10 years (see Table 2-2).

3.2 Integrated CCS solutions at the plant level

In this section, we combine the different stages and mature technologies discussed above, to compile integrated CCS solutions at the plant level. This allows a better understanding of the complexity and costs of capturing, transport and storage or utilization.

Natural gas processing plant and CNG plant

Natural gas is a composition of gases. The main flammable gas is CH_4. It can also contain CO_2, water, H_2S, N_2, heavier hydrocarbons, etc. The composition differs between gas fields. CO_2 fraction can be less than one percent but can also reach 46% of the raw natural gas. When natural gas is processed after extraction, CO_2, water, H_2S, and liquid hydrocarbons are separated in order to increase the quality of the natural gas and to reduce its corrosiveness to infrastructure. CO_2 separation is done usually with absorption, but sometimes with membranes (see Section 3.1) (Shimekit & Mukhtar, 2012).

As CO_2 is often separated in this stage anyway- capturing, transporting and storing it can be performed relatively cheaply and easily. Thus, instead of releasing the separated CO_2 to the atmosphere, CCS can prevent it from contributing to climate change.

CNG production involves only the compression of natural gas to 20–25 MPa (2,900–3,600 psi). Therefore, no CCS is relevant to its production.

Methanol plant

There are more than 100 MeOH plants worldwide, that produce about 100 million metric tons of MeOH per year (2015). Most plants outside of China, use natural gas as feedstocks. Average annual CO_2 emissions are 0.3-0.4 tCO_2e/tMeOH, or 300-400 million metric tons per year worldwide. Due to its expected rising use as vehicle fuel, MeOH production is expected to grow in ~15% in the coming decade (2017-2027) (Collodi et al., 2017).

A techno-economic study on CCU during MeOH production studied production of 5000 tons MeOH/day, from natural gas, through syngas. The CO_2 that is a by-product of the syngas production process is captured and converted using chemical absorption (MEA solvent). While in a conventional MeOH plant the levelized cost of MeOH is 1182 ILS_{16}/tMeOH (274 EUR_{14}/tMeOH), with CCS it is 1290 ILS_{16}/tMeOH (299 EUR_{14}/tMeOH) - only a 9% increase. Note that this price includes CO_2 transport and storage (Collodi et al., 2017).

Moreover, since 2004, MeOH plants in Iran and Saudi Arabia use CO_2 from ammonia plants to boost production (Collodi et al., 2017). This approach can boost production by up to 20%, while reducing energy consumption by up to 5%, and reducing CO_2 emissions (or the amount sent to storage) by 50%. Thus, CCU in a MeOH plant can offset the cost of carbon-capture by increased production and energy savings. It might even be profitable. So, for every 1 tMeOH produced, ~0.175 tCO_2e can be utilized to produce more MeOH, and ~0.175 tCO_2e can be stored.

To calculate the possible reduction in CO_2 emissions from MeOH production and use, we calculate the ratio between their molecular weight:

$$\frac{CO_2\ molecular\ weight}{MeOH\ molecular\ weight} = \frac{44\frac{g}{mol}}{32\frac{g}{mol}} = 1.375 \tag{3}$$

When we multiply this number with 1 tMeOH, we get the weight of CO_2 that is released upon 1 tMeOH combustion. 1.375 tCO_2e are emitted upon 1 tMeOH combustion. If we combine the amount of CO_2 that is released upon MeOH production and MeOH combustion, we find CO_2 emissions from MeOH production and use: 0.175 tCO_2e + 1.375 tCO_2e = 1.55 tCO_2e

1.55 tCO_2e are emitted upon production and use of 1 tMeOH. The percentage of CO_2e that can be captured is: 0.175/1.55=~0.11

Therefore, only ~11% of the potential CO_2 in MeOH production and use can be captured and stored. The rest is released to the atmosphere upon MeOH combustion.

GTL plant

There is not a lot of information on the cost of CCS in GTL plants, mostly because GTL plants are expensive, rare and new. If we consider the full abatement cost in the GTL plant, that includes capturing and compressing CO_2, in 2025 it will be ~300 ILS_{16}/tCO_2e (665 ZAR_{07}/tCO_2e) (Telsnig et al., 2013). This is in the cost range of capturing CO_2 in a NGCC power plant (see Table 3-4 and the NGCC analysis in this section).

However, the GTL process starts with gasification of CH_4 to syngas, and CO_2 is a byproduct of syngas production. Interestingly, the following Fischer-Tropsch reaction that converts the syngas to liquid hydrocarbons, requires the removal of CO_2 from the syngas mixture for an efficient reaction. Thus, the GTL process has a built-in carbon capture stage, even without CCS. This is one of the reasons why a GTL facility has a high capital cost. For full CCS solution for a GTL plant, one needs only to compress, transport and store the separated CO_2 (Jaramillo et al., 2008; Jaramillo et al., 2009; Ou et al., 2013).

As noted before, these are the less expensive phases of CCS, and account for 10-30% of a total CCS solution (Chapman et al., 2013; Folger, 2013). The implication is that if one has already committed to build an expensive, energy-wasteful and polluting GTL factory, upgrading it to have a full CCS solution is relatively not expensive. Also, upgrading it to a full CCS solution can be achieved relatively easily even without prior planning and after the facility completion. The break-even price for carbon capture is only 30.55 ILS_{16}/tCO_2e (6 EUR_{05}/tCO_2e) at a GTL plant gate (van Vliet, Faaij, & Turkenburg, 2009). This is 10 times cheaper than the cost of CO_2e capturing in a NGCC power plant (see Table 3-4).

Thus, compressing CO_2 in the GTL facility, adds only 0.13 ILS_{16}/liter (0.03 USD_{08}/liter) of gasoline or diesel GTL prices, or adds only 173 ILS_{16}/ton of gasoline. This represents an increase of only 5% compared to GTL fuel production cost without compressing CO_2 (Jaramillo et al., 2008), or 3.5% of Israeli petroleum-based production cost (MOE, 2012b).

(Ou et al., 2013) calculated that CCS can reduce CO_2e emissions from GTL life cycle by 37%, from 215 to 135 gr. CO_2e/km. Even though this reduction looks impressive, we should keep in mind that GTL is one of the most energy wasteful fuel types, and one of the largest GHGs emitters over its life cycle per km or liter. GTL with CCS, only reaches CO_2e emissions levels similar to a hybrid electric and internal combustion engine vehicle. GTL with CCS has higher emissions than that of an EV using electricity from natural gas power plants **without CCS** (Ou et al., 2013).

Natural Gas Combined Cycle (NGCC) power plant

A relatively large number of articles have been written on CCS in NGCC power plants. A summary of five main articles that have reviewed dozens of articles in this field, is given in Table 3-4. Usually, a post combustion amine absorption technology is considered in NGCC power plants.

Adding a carbon capture facility to a power plant adds capital cost to the power plant. Also, it lowers the efficiency of energy production, because a large portion of the energy produced is used for carbon capture and is not distributed outside of the power plant. This elevates the operational costs as well. The capital cost of NGCC power plants with CCS ranges between 7700-9000 ILS_{16}/kW. This is an 80-150% increase compared to NGCC power plants without CCS. The COE is elevated by

30-60% to 360-436 ILS_{16}/MWh (without transportation and storage). The COE range with onshore transportation and storage is 250-484 ILS_{16}/MWh, while offshore transport and storage can elevate the COE to 821 ILS_{16}/MWh.

The Cost CO_2e avoided for carbon capture only is 140-680 ILS_{16}/tCO_2e. For the full CCS solution, it is 230-570 ILS_{16}/tCO_2e for onshore transport and storage, while offshore transport and storage can elevate it to 1400 ILS_{16}/tCO_2e.

Coal power plants with CCS, have similar COE as natural gas ones. Interestingly, because the coal emits much more CO_2 compared to natural gas, coal power plants with CCS are more cost-effective and can capture a ton of CO_2 for half the price of a natural gas one (Rubin et al., 2015)

Therefore, if a country wants to reduce as much CO_2 emissions as possible using CCS for the lowest price, it should use CCS in coal power plants and not in natural gas ones.

Summary

CO_2 capture and storage during natural gas processing is a relatively easy and cheap option, when the raw natural gas contains a large fraction of CO_2. No CCS is relevant for CNG production.

Among the solutions that match the FCI options for introducing natural gas-based transportation fuels to the Israeli market, the cheapest solution is to build a MeOH plant with integrated CCU (see Figure 3-2). It can even increase the profit of the MeOH plant. However, MeOH CCU is expected to reduce only 11% of the CO_2e emissions associated with MeOH production and use (see Figure 3-3).

The GTL solution is also interesting, as it is quite cheap to implement (see Figure 3-2), especially when considering the GTL plant high capital cost. It can reduce 37% of GTL life cycle CO_2e emissions (see Figure 3-3).

If a substantial reduction in CO2e emissions is desired, it can be carried out through NGCC power plant CCS. It will increase the COE by 30-70%, but will reduce power plants CO2e emissions by 88%, for electricity power generation and transportation systems (cars, trains, buses and of all electricity). Note that in a life cycle perspective, this reduction is only 65% of all GHGs emissions (due to emissions from infrastructure, fuel production and transport, etc.) (see Figure 3-3). The added value of electric transportation compared to internal combustion engine transportation, is the absence of local emission of pollutants and lower transportation noise in urban areas. However, per tCO_2 captured, this solution is by far the most expensive (see Figure 3-2). It has to be noted that costs presented in Figure 3-2 do not include transport and storage, which is the same for all facilities per tCO_2.

Since research on MeOH, GTL and CCS is limited but promising, it is advisable to study their implementation in Israel. It is also advisable to review this information further over time to compile new data that may become available.

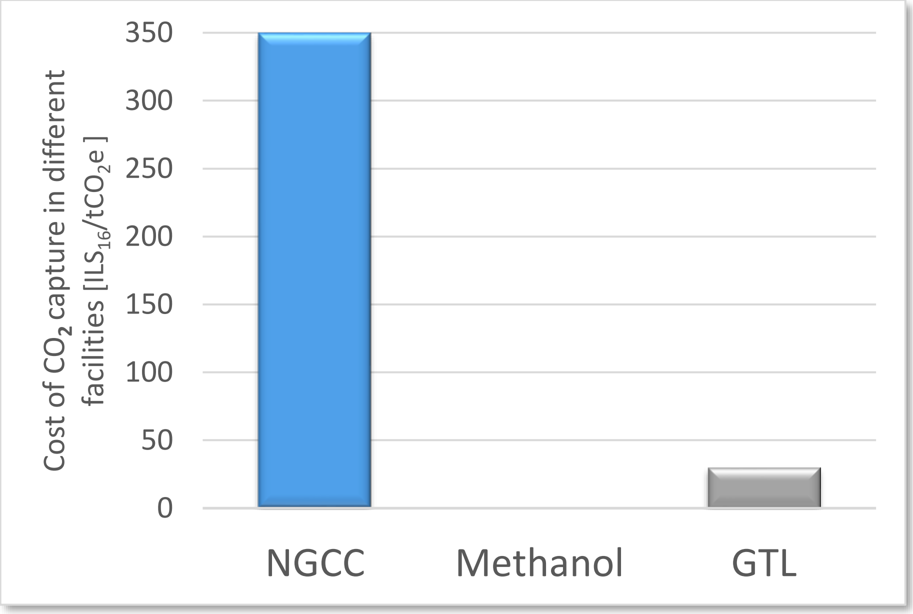


Figure 3-2 > The cost of capturing CO_2 in natural gas-based transportation fuel substitute's facilities

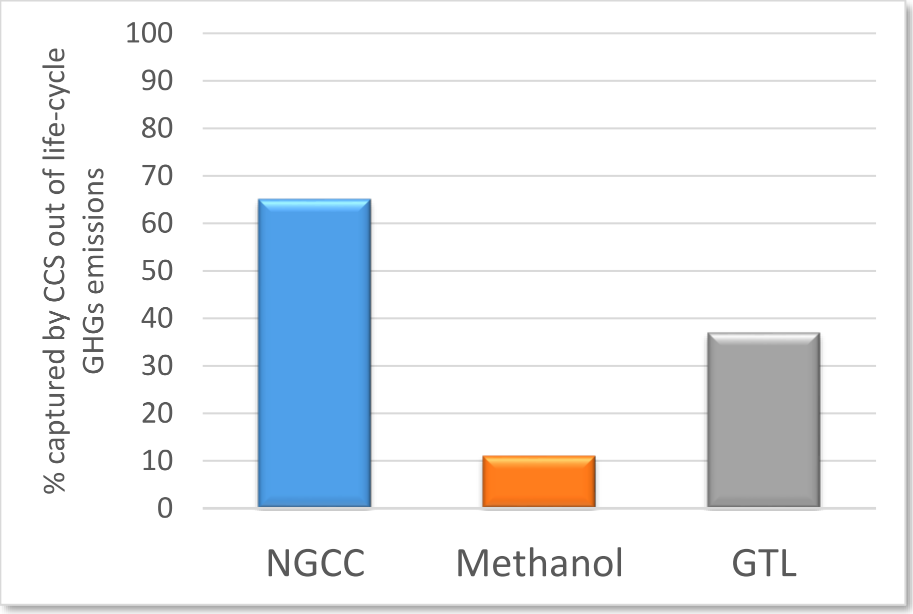


Figure 3-3 > The percentage of life-cycle GHGs that CCS can capture in natural gas-based transportation fuel substitute's facilities

4 POLICY OVERVIEW

4.1 Policies review

Achieving emission reduction targets at the lowest cost requires that all emission reduction technologies are deployed in order of their relative cost effectiveness. Such an outcome is best achieved through policies that are technology neutral. Among such technologies, CCS has an important role in the reduction of CO_2 emissions through 2050 if we are to limit the rise in global temperature to 2 degrees Celsius at the least cost (IEA, 2016b). To achieve that, the deployment of CCS needs to be rapid and widespread across many nations around the world.

As is the case with other emission reduction technologies, targeted polices and increased investment will be needed to put CCS on the path to deployment. Until 2015, the total investment in CCS has been less than 1% of the total investment in renewable power generation technologies (predominantly wind and solar PV) (GCCSI, 2015a). This may reflect - in part - that CCS has not been afforded comparable policy support and much more effort is required to encourage further deployment.

Four key pillars that would drive investments in CCS as a low-carbon technology (Consoli et al., 2017; GCCSI, 2016):

1. *A predictable and enduring policy environment,*
2. *Effective and comprehensive CCS law and regulation,*
3. *Early storage site identification and site characterization,*
4. *Research and Development (R&D) targeting cost reduction of CCS technologies.*

The Global CCS Institute (GCCSI) developed a readiness index which quantifies the extent to which a country has created an enabling environment for investment in the wide-scale, commercial deployment of CCS. A nation's readiness is based on an aggregation of scores from four sub-indicators:

1. **Inherent interest** – due to the country's high emissions or consumption and/or production of fossil fuels.
2. **Legal and Regulatory** — frameworks which are critical to the regulation of CCS. These can include environmental assessments, public consultation and long-term-liability.
3. **Policy** — this includes direct support for CCS as well as broader implicit support through measures such as carbon pricing, research or project funding and initiatives.
4. **Storage** — based on geological and technical aspects that could impact a storage project within the borders of that country, including the geology, the maturity of storage assessments and technical ability to store CO_2.

The analysis reveals that a significant amount of government and private sector activity has been focused on CCS technology development, particularly the capture and storage of CO_2, which are now mature technologies. Less emphasis has been placed on the two components that drive investments, which are a supportive policy environment driving CCS, and legal and regulatory frameworks that enable the projects to proceed. This may reflect the desire of policy makers to examine the technical feasibility of storage and other aspects of CCS prior to implementing policies and legislation to support fuller deployment of CCS.

CCS Policy Indicator for Select Countries

When focusing on the policy indicator, the majority of countries in the GCCSI analysis, have low scores[21] (see Figure 4-1). This finding is not surprising since CCS does not receive equal policy support compared to other GHG mitigation technologies such as renewable electricity generation. The policy indicator described is a relative measure, reflecting the fact that there are currently no countries with policies that are sufficient to encourage deployment of CCS at a large scale. However, significant differences can be observed between countries according to their policy indicator ranking (Consoli et al., 2017):

- Countries with relatively higher scores (Canada, Netherlands, Norway, UK and the US) have employed a broad range of measures to pursue climate change targets. Governments in these countries have also made consistent statements that identify the important role of

---

[21] Low score means few or no policies regarding the role of CCS in overall climate change policy, as well as, little inherent CCS interest, while a high score expresses the opposite trend.

CCS alongside other low and zero emission technologies. Investment in CCS projects and research is supported via a combination of legislated requirements, market-based incentives and supportive institutional arrangements. Also, direct regulation of emissions from power plants, encourages the deployment of CCS in this sector. It is important to emphasize that the global investment in CCS is by far lower than global investments in clean energy technologies (20 B$ and 2,500 B$, respectively) (IPIECA, 2018).

- Countries that score moderately have fewer direct policies with regard to the role of CCS in overall climate change policy. Some of these countries have CCS projects in the operational stage, yet without significant direct subsidies, and rely upon CO_2-EOR to make the projects commercially viable. Many mature industrialized countries score moderately, including member states of the European Union (EU) that register policy observations such as overarching strategies and political statements regarding CCS, as well as funding mechanisms and the Emissions Trading System (ETS) which are also broadly applicable to CCS.
- Countries with lower scores have not developed clear policies on the role of CCS as a specific GHG mitigation technology.

The GCCSI notes that all countries are expected to improve in policy rankings over time in line with high levels of ambition sought under the United Nations Framework Convention on Climate Change (UNFCCC's) arrangements, and as commitments to limit global temperature rise translate into detailed policy action.

Figure 4-1 presents schematically the results of the latest update of the CCS policy indicator (CCSPI), reflecting data by mid-2015 (GCSSI, 2015a). The size of the bubbles in the figure reflects the large-scale integrated project (LSIP) activities in the countries. The schematic in the figure focuses on the link between the policy indicator and the country's interest in CCS. Three countries, United Kingdom, the United States and Canada have a strong inherent interest with respect to CCS and have implemented - or are about to implement - various key policies that support large scale deployment. China also has a high degree of inherent interest and continues to demonstrate relatively strong policy support for CCS through R&D as well as partnerships with various countries around the world. Countries in the EU demonstrate varying degrees of inherent interest reflecting diversity in their consumption and production of fossil fuels. EU policy on CCS covers a broad range of supporting categories including market pricing, legislative frameworks and direct funding.

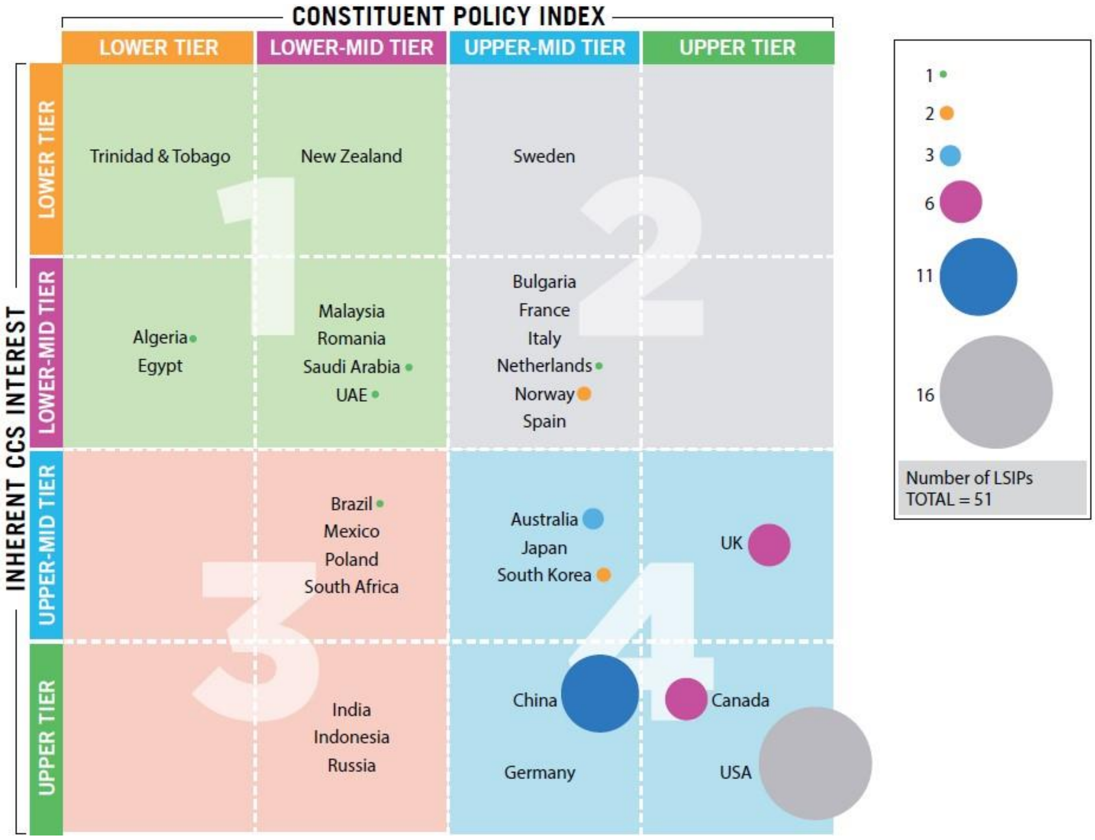


Figure 4-1 > CCS Policy Indicator 2015 Results
(GCCSI, 2015a)

Reviewing countries and their scores across the three indicators (Legal and Regulatory, Policy and Storage) demonstrate that policies (including emission mitigation targets) that identify CCS as a low carbon mitigation technology and incentivize investment in CCS, are the most effective drivers of CCS deployment. Further, policy and effective regulation remain the leading drivers of CCS deployment even where the CO_2 is used for EOR.

Conversely, the lack of clear CCS policy is the primary reason why numerous countries with prospective storage potential and amenable regulatory frameworks have not built large-scale CCS facilities. In 2015, the United Kingdom had the strongest policy leadership in encouraging CCS which resulted in two leading CCS facilities and the prospect for many others (GCCSI, 2015b). The UK has a market-based mechanism in the form of a carbon price floor which supports these investments. But it was a relatively strong long-term commitment to CCS and direct funding that provided the greatest incentive for deployment. This commitment though was removed in late 2015 resulting in the termination of the two leading projects.

The GCCSI concludes that there is correlation between high CCS Index scores and deployment (GCCSI, 2016). The highest-ranking nations in the CCS Index host all but four of the 22 large-scale projects that are operating or under construction which are recognized by the Institute. It is important to note that of these projects the majority are associated with CO_2-EOR. Moving forward, six large-scale projects (operational or under-construction) that are not CO_2-EOR projects and are directly related to emissions reduction are also all hosted by high scoring nations.

The two Norwegian projects suggest that a modest but stable price on carbon (US$64/t$CO_2$e as of January 2018) can be an effective driver for CCS deployment with dedicated storage, while direct regulation was a key factor in the Gorgon project in Australia (also with dedicated storage).

Algeria, Brazil, Saudi Arabia and United Arab Emirates do not have overall high scores, but each has one large-scale project operational or under construction. These projects show that country-specific factors within the CCS Index criteria do not need to be all satisfied to encourage CCS deployment. This finding is reinforced by the fact that many projects have been enabled via CO_2-EOR revenues and in relatively low cost CCS applications such as natural gas processing.

Unique challenges for CCS deployment:

A recent publication (Consoli et al., 2017; GCCSI, 2017) emphasizes the uniqueness of the field and claims that unlike many other low-emissions technologies, CCS deployment faces unique challenges, requiring tailored policy solutions:

- **Predictability in policy setting is paramount**: CCS facilities typically involve very large capital investments, have long gestation periods and asset lives, thus a stable policy environment is essential.

- **Need for multi-industry focus**: CCS will need to be applied across various industries, and thus policy must accommodate different emission footprints, markets and cost structures.

- **Commercial integration across all three elements of the CCS chain**: CCS deployment typically involves multiple actors across the value chain and aligning interests has proved challenging in many projects and made financing difficult.

- **Early identification and characterization of suitable geological storage sites**: consistent with the roll-out of historical industrial infrastructure, there is little prospect of CO_2 transport and storage infrastructure being developed privately if strong policy incentives are not put in place.

- **Legal and regulatory regimes that provide clear obligations and liability provisions**: this especially concerns storage activities and must be designed to accommodate the thousands of facilities that will need to emerge over the course of the next few decades.
- **Robustness in R&D efforts**: various CO_2 capture methods exist and are being refined and newer, potentially much lower cost techniques, are being tested at pilot scale. Choices for wide spread deployment are dependent on robust R&D support.
- **Increasing community awareness of the importance of CCS:** social license issues that associate CCS with polluting fuels and industries, must be addressed.

Accordingly, the GCCSI indicates several reinforcing elements of the policy-making process that are critical to accelerating the deployment of CCS. These include:

- Setting of credible and economy-wide emissions reduction targets, consistent with the aims of the Paris Agreement.
- Designing policy, including economic incentives (to promote energy efficiency, renewable energy and incentivizing construction of CCS plants. Negative incentives can include carbon tax) to achieve medium-term emissions reduction in a range of sectors and in line with these longer-term targets, combined with measures that meaningfully deal with or compensate those who lose from transitioning to a low-carbon future.
- Explicitly including CCS in national climate action plans or similar flagship policy statements, which either implicitly or explicitly acknowledge how CCS can play a role alongside other low carbon technologies.
- Securing policy certainty via a government commitment that has been demonstrated to extend beyond political cycles and to be resilient to conflicting political demands.
- Establishing (region-relevant) public/private business models that better manage risk allocation between the capture, transport and storage elements of the CCS chain, thus reducing overall risks.
- Devoting special attention to accelerating investment in storage exploration and characterization, in view of the long lead times for development in certain regions.

Industrial CCS

Beyond the barriers faced by CCS in general, such as those related to legal frameworks and public perception, there are important areas to be addressed for the wider deployment of CCS in industry (IEA & UNIDO, 2011). Governments should establish an overall policy strategy and pathway for CCS in industry, incorporating the necessary RD&D priorities, incentivizing policy mechanisms and enabling legal frameworks. As discussed below in Section 4.3., raising awareness of CCS is particularly important for industrial applications of CCS, apart from power-related CCS. Governments and industry should, together, pursue large-scale demonstration projects for CCS in industry in national or regional demonstration programs.

Industry will not adopt CCS without incentives and regulatory mechanisms, which governments should tailor to the maturity of the technology and its development over time. For immature technologies, incentives need to be directed towards technology learning, whereas incentives for mature technologies can be more generic, or technology-neutral, and should aim to achieve CO_2 emission cuts. Timing of this change in policy focus is difficult to predict, because it will depend on how CCS and alternative technologies mature. However, good government policy would outline a pathway for policy evolution, a stable policy framework with clearly defined break points or “gateways” can offer flexibility to government and some certainty to investors. This may lead to lower costs of finance, greater R&D expenditure and more effective infrastructure planning and coordination.

Five factors may justify policy intervention in markets where CCS could be deployed: externality, public good, imperfect competition, information asymmetry and imperfect information, and complementary markets (IEA, 2012). Effective support for CCS calls for a combination of policies, where each policy addresses a separate dimension of market failure. Yet, policy makers should be aware that using more than one instrument towards the same end may have unintended consequences.

A review of incentive mechanisms for CCS in industry is presented in Table 4-1:

Table 4-1 > Incentive mechanisms for CCS in industry

Policy incentive	Applicable Policy Measures	Pros	Cons	Examples
Sufficiently high and stable global price for carbon emissions	Market-based mechanisms include emissions trading schemes (setting a cap on CO_2 emissions), or imposing carbon taxes	In the long term, expected to deliver the required reductions at the lowest cost to society	May not provide enough incentives to encourage the deployment of new, more expensive technologies in the short term	• Since 1991, Norway taxes CO_2 emissions from its offshore oil and gas industry at a rate of around USD 35/tCO_2 emitted, and it rises over time http://www.npd.no/en/Regulations/Acts/CO2-discharge-tax/ • Some 40 countries and more than 20 cities, states and provinces already use carbon pricing mechanisms as a means of bringing down emissions and drive investment into cleaner options http://www.worldbank.org/en/programs/pricing-carbon
Funding CCS demonstration projects	Investment support (grant, tax credit, loan guarantee, subsidy by trust fund) and production subsidies (guaranteed carbon price, feed-in price, etc.)	Enables kick-starting 'seed projects' to provide a path to technology implementation	Possibility of projects being abandoned if funding is terminated in the future	• Technology development under the CO_2 Capture Project https://www.co2captureproject.org/ • The NETL Carbon Capture Program's R&D https://www.netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/Industrial-Uses-CC-Technologies.pdf • European Commission NER 300 programme. https://ec.europa.eu/clima/policies/lowcarbon/ner300_en • Australian CCS RD & Demonstration Fund https://industry.gov.au/resource/LowEmissionsFossilFuelTech/Pages/Carbon-Capture-and-Storage-Research-Development-Demonstration-Fund.aspx

Policy incentive	Applicable Policy Measures	Pros	Cons	Examples
Technology mandates and standards (command and control instruments)	Require CCS in certain installations or industries as a condition for granting an operating license, prohibit CO_2 venting from large sources of CO_2, sectoral GHG emission intensity standards	Allow project proponents to recommend applicable technology for maximum flexibility	If a specific technology is imposed, would lead to less flexibility to the operator and could result in higher costs of GHG mitigation to society. Unlikely to provide a practical option before technologies are commercially available	• A combination of CCS initiatives at the UK electricity market reform proposals include an emission performance standard (EPS), so that no new coal-fired power stations are built without CCS https://www.gov.uk/government/publications/planning-our-electric-future-a-white-paper-for-secure-affordable-and-low-carbon-energy • Limitation on long-term investments in baseload generation by the state's utilities to power plants that meet a non-tradeable EPS of 1,100 lbs CO_2 per MWh http://www.energy.ca.gov/emission_standards/

The IEA (IEA, 2012) illustrates the shift over time in the various layers of policy approach:

- **From capital to operating incentives** - Over time, risks surrounding the technology will diminish and the regulatory and policy framework will become better established and understood. If expectations are realized, capital support can decline and make way for a greater emphasis on operating support (i.e. incentive mechanisms to provide additional revenue for each unit of output where a CCS unit is operational).
- **From public funding to private incentives** - At the initial stage, government involvement can facilitate learning opportunities and promote co-ordination between firms, which will facilitate more efficient infrastructure development. Over time, tougher emissions targets will translate into higher compliance costs and make it more important for policy to stimulate the most cost-effective forms of abatement.
- **From subsidizing abatement to penalizing emissions** - In the early phases of deployment, subsidies and quantity mandates may be appropriate to encourage commercial firms to invest more than they otherwise would. As learning progresses, the key aim of CCS policy will be directed towards providing incentives for emissions reduction. Then penalties may suffice to stimulate more cost-effective CCS.
- **From technology-specific to technology-neutral policies** - Early objectives of CCS incentive policy are to promote the technology, to determine its technical viability, and to demonstrate that it is an affordable option when deeper emission cuts are required. Once these three objectives are achieved, the main aim becomes abatement at the lowest possible cost. This is best achieved through a technology-neutral instrument, which leaves the market to select the most cost-effective abatement options.

The quality of the policy matters a great deal – at two levels: overall policy architecture and selection of policy instruments. Policy architecture refers to the overall policy framework – the vision and main structural elements and how they fit together. It encompasses a range of policy instruments, with each chosen instrument designed to respond to a particular policy objective over time. Together these instruments can comprehensively improve the conditions for uptake of CCS technology in a way that suits the market environment.

Implementation Obstacles – A U.S. Example

Although a potentially useful climate change mitigation tool, CCS efforts in the United States remain mired in demonstration and development. Prior studies suggest numerous reasons for this stagnation, which were examined using an anonymous opinion survey completed by 229 CCS experts (Davies et al., 2013). The survey results are shown in Figure 4-2.

Davies et al. (2013) identified four primary barriers to CCS commercialization:

1. *cost and cost recovery,*
2. *lack of a price signal or financial incentive,*
3. *long-term liability risks, and*
4. *lack of a comprehensive regulatory regime.*

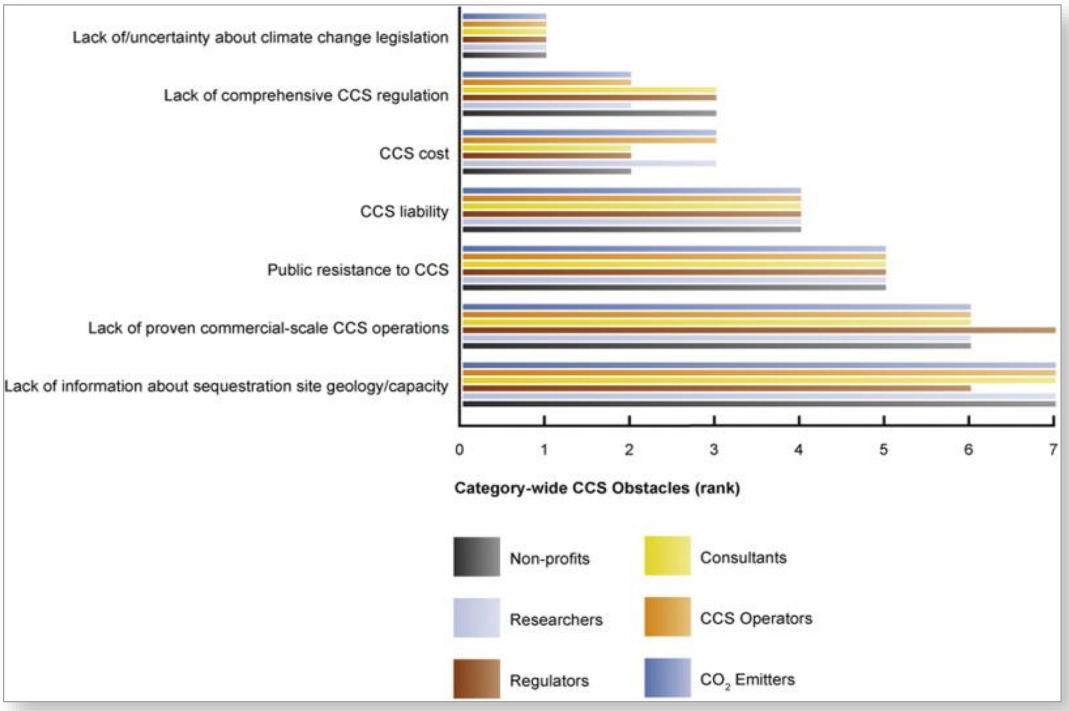


Figure 4-2 > Ranks of Obstacles to CCS Implementation in the US (Davies et al., 2013)

These results give empirical weight to previous studies suggesting that CCS cost (and cost recovery) and liability risks are primary barriers to the technology. However, the need for comprehensive rather than piecemeal CCS regulation represents an emerging concern not previously singled out. The results clearly show that the CCS community sees fragmented regulation as one of the most significant barriers to CCS deployment. Specifically, industry is united in its preference for a federal regulatory floor that is subject to state-level administration and sensitive to local conditions. Likewise, CCS experts share broad confidence in the technology's readiness, despite continued calls for commercial-scale demonstration projects before CCS is widely deployed.

CCS Technology Demonstration - UK Example

CCS technology has been endorsed by the IPCC, but it requires country specific technology roadmaps for implementation. Figure 4-3 below presents technical and financial issues and non-technical topics that need to be addressed during the country-specific CCS demonstration period, which is an essential step for moving to commercialization. Five consensus conclusions emerge from the UK experience (Gough et al., 2010):

1. *The need for a monetary* CO_2 *value and the financing of CCS schemes;*
2. *No technical barriers to the deployment of a demonstration scale CCS plant;*
3. *The role of demonstration projects in developing a robust regulatory framework;*
4. *Key Carbon storage issues;*
5. *The need for a long-term vision in furthering both the financial and non-technical development of CCS.*

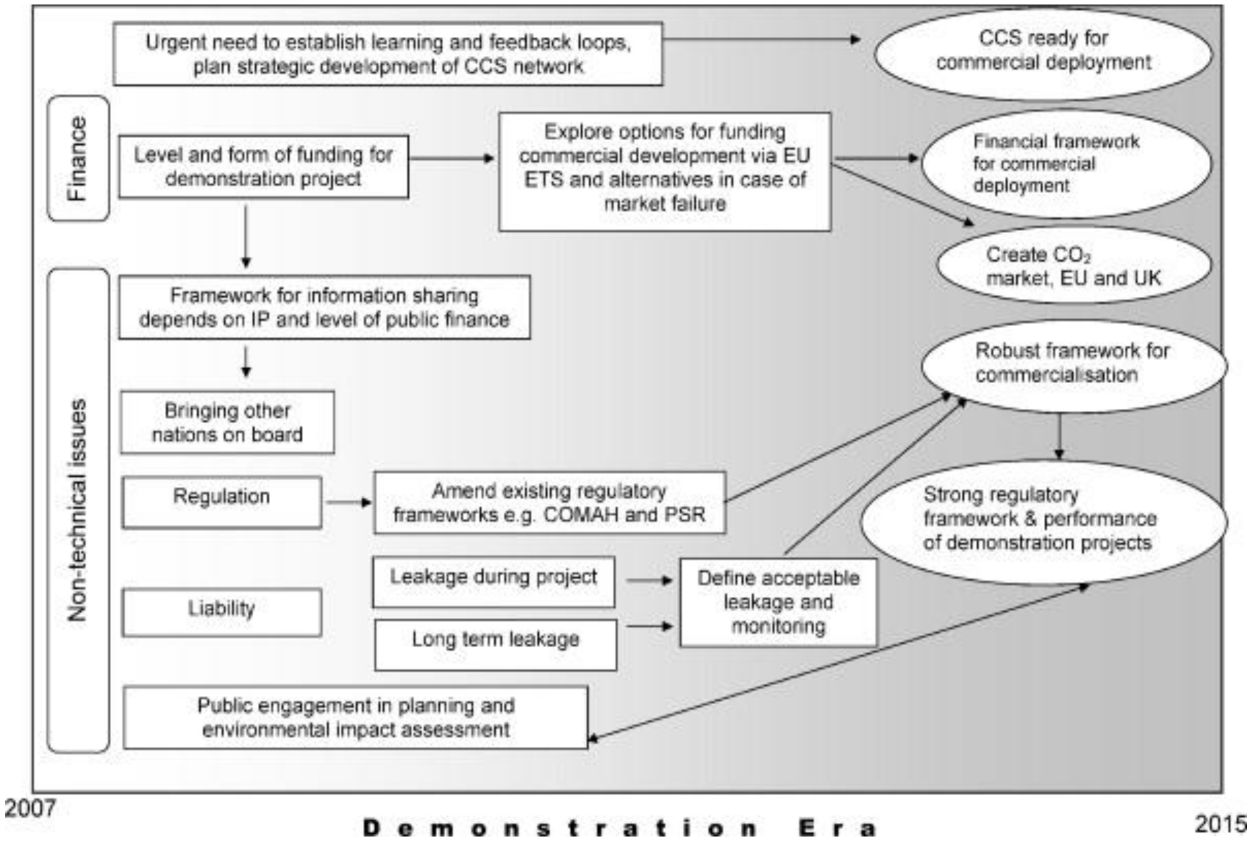


Figure 4-3 > Financial and Non-Technical Issues to be addressed prior to Commercialization (Gough et al., 2010)

Linkage to Current Global Policy

The challenge posed by climate change mitigation will require a fundamental decarbonization of the global energy system. If CCS can be deployed at scale, it will be possible to extend and more gradually reduce the use of fossil fuels while simultaneously lower the costs of this potentially disruptive transformation.

A recent study supports and expands upon past work by reviewing the value of CCS under current scenarios defined by the latest global NDCs commitments through 2030, and possible extensions through the end of the century (Davidson et al., 2017). Results from this study suggest that CCS can provide significant value in reducing the overall cost of mitigating climate change and, to the extent that cost savings ease the societal burden of mitigation, could improve the chances of achieving stabilization of atmospheric CO_2 concentrations at a level that results in fewer negative consequences to society. The authors make it clear that a sense of urgency is needed regarding the scale and timing of technological shifts required to address the most recent climate targets agreed upon in the Paris Accord. This can only be achieved if technologies, institutions, markets and infrastructure will be ready to support its deployment at levels that dwarf the scale of commercial CCS to date.

CCS deployment is important both to electricity generation and to the manufacturing of liquid fuels (Muratori, 2017b). To make CCS viable across applications and technologies greater scrutiny of CCS cost assumptions is recommended. This should include broader assumptions about the practical barriers to CCS deployment – including behavioral change – which will be important to facilitate and further refine scenarios of energy system transformation.

4.2 Environmental impact

Installing CCS technologies in energy production and industrial facilities to reduce CO_2 emissions clearly reduces GHG emissions and the negative impacts of these emissions on climate change. However, as in almost every human activity, CCS technologies could have negative environmental impacts as well.

It is recognized that efforts to control emissions of GHGs or air pollutants in isolation can have either synergistic or antagonistic effects on emissions of the other pollutant groups. In the case of

CCS, the use of CO_2 capture technology in power plants leads to a general energy penalty in the order of 15–25% depending on the type of capture technology applied. This can result in negative consequences due to additional 'direct' and 'indirect' emissions of GHGs and air pollutants, offsetting the positive direct effect of CCS technology which has (substantially) the biggest potential of reducing CO_2 emissions.

Overall, and depending upon the type of CO_2 capture technology implemented, synergies and trade-offs are expected to occur with respect to the emissions of the main air pollutants NO_x, NH_3, SO_2 and PM.

Air Pollution Impacts from CCS

Key findings from an EU survey (EEA, 2011):

- Increases of direct emissions of NO_x and PM are foreseen to be in the order of the fuel penalty for CCS operation, i.e. the emissions are broadly proportional to the amount of additional fuel combusted;
- Direct SO_2 emissions tend to decrease since its removal is a technical requirement for CO_2 capture to take place to avoid potential reaction with amine-based solvents;
- Direct NH_3 emissions can increase significantly due to the assumed degradation of the amine-based solvent used in post-combustion capture technologies;
- Indirect emissions can be significant in magnitude, and exceed the direct emissions in most cases for all pollutants;
- The extraction and transport of additional coal contributes significantly to the indirect emissions for coal-based CO_2 capture technologies, with other indirect sources of emissions including the transport and storage of CO_2 contributing around 10–12 % to the total;
- Power generation using natural gas has lower emissions compared to coal based power generation, directly as well as indirectly. The switching from coal- to gas-fired power generation can have larger impacts on the direct and indirect emissions of air pollutants, depending on the technologies involved, than the application of CO_2 capture technologies.

Based on these findings, CCS technology may be considered to fall into a category of technologies that are considered to be ‘generally beneficial both for air quality and climate change’. However, due to the potential increase in emissions of certain air pollutants (e.g. NH_3, NOx and PM) CCS could not be ranked very high as 'beneficial for air quality'.

Key findings from GCCSI (GCCSI, 2017):

deployment of CCS technologies can deliver significant reduction in conventional atmospheric pollutants:

- A 90% reduction in sulphur oxide emissions can be achieved (through integrated flue gas desulfurisation);
- A reduction of over 70% in nitrogen oxides emissions (from selective catalytic reduction);
- 100% removal of fly ash from electricity generation (electrostatic precipitators and fabric filters), which can be recycled for use in the construction industry;
- Heavy metals (mercury) and particulate matter can also be effectively managed.

As mentioned before (Chapter 3), adding carbon capture technologies to processes may have significant impact as it:

- Usually increases the energy demand of the system, and therefore increases the use of fossil fuels,
- May require the use of CO_2 solvents with limited recoverability,
- Could lead to the use of huge amounts of water for carbon capture, and
- Requires additional dedicated infrastructure.

Increased energy demand: Since most energy sources used today (globally and in Israel) are still fossil fuels based, on average, increasing the energy demand of a system will raise fossil fuels use. For example, adding CCS to a NGCC power plant increases the fuel demand of power plants by 16% (Sathre et al., 2011). There are emissions associated with fossil fuels that are emitted outside of the power plants (mining operations, shipping, CH_4 emissions, etc.). So, even though CCS allows capture of 90% of the emitted CO_2 from the power plant, the increased energy demand and its associated emissions allow reduction of only 65% of the GHGs emissions for the life cycle of using natural gas for electricity (Cuéllar-Franca & Azapagic, 2015; Sathre et al., 2011). The real numbers are probably even lower, as this study did not take into account the discovery that CH_4 emissions from natural gas system are much higher than previously assessed (Howarth, 2014; Lavoie et al., 2017; Petrenko et al., 2017; Schneising et al., 2014; Worden et al., 2017).

An increase in fossil fuels use also increases underground\fresh\salt water pollution due to petroleum\CH_4\wastewater leaks and accidents.

CO_2 solvents: The prominent CO_2 capture technology today, CO_2 absorption, is the least environmentally friendly technology when compared to other capture technologies that are in various stages of development. The life-cycle of the solvents is usually energy intensive, with substantial emissions. Often, these solvents cannot be recovered efficiently, and needed to be supplemented with fresh solvents. Therefore, major improvements are needed in the field to mainstream the use of more environmentally friendly CO_2 capture technologies.

Increased water demand: Water is used in CCS as a solvent and to cool\conduct heat. In England, CCS in power plants is expected to almost double the water use of coal power plants. In natural gas power plants, CCS elevates the water use by 10-15% per GWh (Byers, Hall, Amezaga, O'Donnell, & Leathard, 2016). In Israel, it would be significant mostly for the inland power plants that are cooled with freshwater. However, for most Israeli power plants that are located on the Mediterranean shoreline, and use sea water for cooling, the environmental impact would be lower.

Dedicated infrastructure: CCS facilities require dedicated infrastructure in addition to power plants and industrial facilities, including for CO_2 capture installations, plants for CO_2 utilization, and pipelines for conveying CO_2, and CO_2 storage (sequestration) facilities. This additional infrastructure will require the use of more cement and steel, construction of additional roads, and other relevant installations to support such operations. The incremental increase of infrastructure may include operations that would be carried out by using coal powered electricity or petroleum-based transportation fuels. Therefore, these operations may lead to incremental emissions of air pollutants that are characteristic of such sources including heavy metals and other pollutants (Singh, Strømman, & Hertwich, 2011).

When comparing regular NGCC power plant to those with added CCS, the major negative environmental effects include (Cuéllar-Franca & Azapagic, 2015; Sathre, Chester, Cain, & Masanet, 2012; Singh et al., 2011; Zapp et al., 2012):

- Increased Human Toxicity (HTP) by 125%. Infrastructure demand contribute 84% of this increase (almost all of the 125% increase), due to heavy metals emissions associated with material production. Other important causes are CO_2 capture system emissions (amines, formaldehyde, and acetaldehyde).

- Increased Fresh Water Aquatic Ecotoxicity (FWAE\FAETP\FETP) by 165%. 84% of the increase is associated with waste treatment process. 6% of the increase is associated with amines (CO_2 capture solvents) production chain.
- Increased Marine Aquatic Ecotoxicity (MAE\MAETP) by 150%. 47% of the increase is due to the waste treatment process, 38% is due to infrastructure, and 9% is due to amines production.
- Increased Terrestrial Ecotoxicity (TEP\TETP) by 145%. 56% of the increase is due to infrastructure development, and 16% is due to amines emissions from the CO_2 capture process.

Additional more limited environmental effects of incorporating CCS into process include:

- Increases Eutrophication (EP\MEP) by 35%. Mostly due to higher NO_x emissions from increased fuel combustion. Increased Photochemical Oxidation (POP\POCP) by 20%. Mostly due to higher NO_x emissions from increased fuel combustion (45%), and from increased CH_4 and SO_2 emissions from natural gas production chain (40%).
- Increased Acidification (AP) by 45%. Mostly due to higher NO_x emissions from increased fuel combustion.
- Increased Cumulative Energy Demand (CED) by ~20%. Mostly due to the CO_2 capture process.

The use of CCS technologies does not seem to significantly affect Abiotic Resource Depletion (ABD) and Ozone layer Depletion (ODP) (Sathre et al., 2012; Zapp et al., 2012). As far as air quality impact, adding CCS technologies to NGCC power plants is expected to increases air emissions of NOx, SOx, PM, NH_3, CO, VOC, Pb and Hg, by 8-28% (Sathre et al., 2012).

All the numbers above are for the most suitable NGCC CCS solution for Israel: NGCC power plant, carbon storage in onshore deep saline formations (see Figure 4-4).

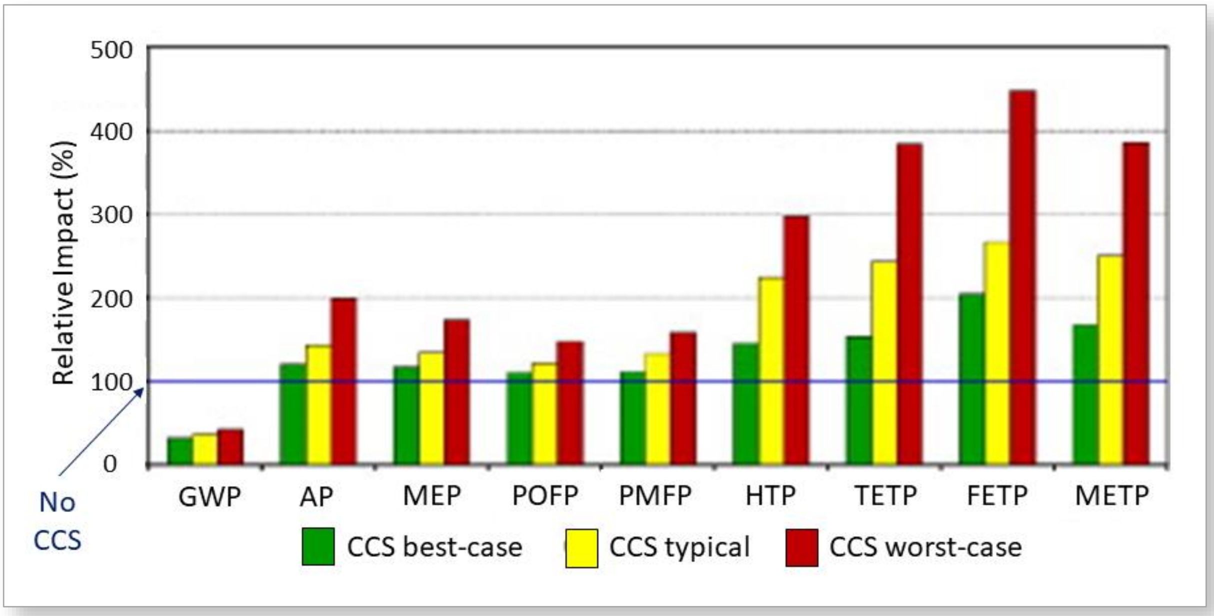


Figure 4-4 > Comparative environmental impacts of adding CCS to a NGCC power plant (Adopted from Singh et al. (2011))

The calculated environmental impact: Global Warming Potential (GWP), Acidification (AP), Eutrophication (MEP), Photochemical Oxidant Formation Potential (POFP), Particulate Matter Formation Potential (PMFP), Human Toxicity (HTP), Terrestrial Ecotoxicity (TETP), Fresh water aquatic Ecotoxicity (FETP), Marine aquatic Ecotoxicity (METP).

The blue line (Figure 4-4) at 100% is the environmental effect of NGCC without CCS. The bars are environmental effect of NGCC with CCS. Clearly the best CCS technologies will have lower environmental impacts but it is difficult to fully assess whether the negative **local** environmental impacts are compensated by the positive **global** impacts on climate change, as evidenced by the lower global warming potential for all CCS cases.

It is assessed that the environmental impacts of adding CCS\U to MeOH and GTL plants would be much lower when compared to the impacts mentioned above. This is due to the fact that GTL plants already include the CO_2 capture stage as part of the GTL\MeOH production processes. Since this stage has the most environmental impact within CCS\U operations chain, it would therefore only require the addition of CO_2 compression, transport and storage (Jaramillo et al., 2008, 2009; Ou et al., 2013). In MeOH plants, CCU reduces the energy consumption by 5% and increase production by 20%. So, per tMeOH produced, the environmental impact can be even lower compared to a MeOH plant without CCU (Collodi et al., 2017).

Storing CO_2 in deep saline formation, as with other deep underground injection, has the potential to compromise the underground fresh water reservoirs. Also, like underground injection of produced water, injecting CO_2 underground can increase earthquake occurrence frequency. Most of these earthquakes are low magnitude (<4 magnitude) that do not cause damages. A few earthquakes (out of hundreds) are between magnitudes 4-6, can cause damages but are rarely fatal (Hornbach et al., 2015; Keranen, Savage, Abers, & Cochran, 2013; McGarr, 2014; Raleigh, Healy, & Bredehoeft, 1976).

To make things more complicated, CCU GHGs emissions are usually higher compared to CCS, but its environmental impacts are lower (Cuéllar-Franca & Azapagic, 2015).

Notably, these environmental effects are additive to the present environmental effects of energy production though they do mitigate GHG emissions from the use of fossil fuels. The alternative route for reducing CO_2 emissions from energy production - using low carbon energy sources (renewables, nuclear energy), not only emit less GHGs compared to fossil fuels + CCS, but also performs better on most other environmental factors mentioned above (Hertwich et al., 2015). Only in some resources depletion (e.g. iron, copper, and cement), does fossil fuels + CCS performs better than low carbon energy sources.

4.3 Public awareness and engagement

CCS is one of the strategies that would have to be utilized in order to reduce GHG emissions and avoid the resulting and dangerous effects of climate change from continued use of fossil fuels (IEA, 2013).

For CCS to be implemented on the scale necessary, efforts are needed to be undertaken in order to inform and raise awareness among the general public about CCS. The public needs to know what exactly CCS is, how it works and what are its pros and cons. Broad public awareness of CCS' effectiveness will help alleviate concerns, promote positive opinions and encourage the engagement of the communities where CCS projects are planned to be undertaken (Pietzner et al., 2011).

Surveys suggest that most members of the general public are unaware of advanced technologies like CCS. Further, those people who are aware of the term tend to have little understanding of the concept. This lack of awareness has become an increasing focus of policy makers internationally, and a number of governments have developed communication strategies to raise awareness of CCS and other low emission technologies and to help promote social acceptance of these technologies (Ashworth et al., 2009).

CCS is regarded as an important bridging technology to a sustainable energy production. Whether it will be deployed on a large scale depends on both technological advances and social processes. Public perception of CCS can be crucial, and research interest in this topic has been growing. This interest has led to the publication of a “Public perception of carbon capture and storage (CCS): A review” in which 42 articles were identified (L'Orange Seigo et al*.,* 2014). The review analyzed lay people's concerns and spontaneous reactions to the technology and the results form a good basis for risk communication about CCS, as will be discussed further below.

Since CCS infrastructure and storage sites will be vital for implementing the technology, it may mean that pipelines may have to run through, or close to, populated areas and storage sites will be located under such areas. Although science and technology have evolved in recent years and many issues relating to public safety have been resolved, there are still issues relating to the risks of CCS that need to be explained and publicly discussed in order to calm public concerns. This could be achieved by assembling a Community Advisory Panel (CAP) consisting of a group of individuals who live near or around the expected CCS project, who represent the fabric of their community, and the management of the CCS project. The CAP, aimed to be a forum for open and honest engagement and dialog between the community and the project’s management, should meet regularly to discuss common issues of mutual interest and should be run by individuals trusted by all participants (WRI, 2010).

There are two aspects to developing public awareness about CCS and working with communities where CCS projects are planned to be located. These are social research and communication. Social research is important to inform governments, develop policy and formulate communication strategies. Good communication is vital to a CCS project and whether that project proceeds (Bartlett, GCCSI).

The best predictor of acceptance of CCS is the perception of benefits as is typical for the acceptance of new technologies (Wallquist et al., 2012). In the case of CCS, the benefits are intrinsically linked to the continued use of fossil fuels for electricity production, while attaining the additional benefit of reducing CO_2. People feel a strong need to view CCS in context and want to know about other alternatives.

1. **Perceived Public Concerns about CCS**

In studies conducted by Ashworth et al. (2007 and 2009) the following were noted as perceived public concerns about CCS:

- Safety risks of a CO_2 leak.
- The risk of contamination of ground water.
- Any harm to plants and animals near storage sites.
- Assumption that CO_2 is explosive.
- Is it the wrong solution for climate change, a band aid?
- Are there enough available storage sites?
- It appears to require a large infrastructure which does not necessarily exist today.
- Long term liability issues.
- Cost – economic efficiency.
- Scale required for successful CO_2 mitigation.
- It is an unknown technology.
- Should not be pursued at the expense of renewable energy sources.

2. **Perceived Benefits of CCS**

The same study identified the following perceived public benefits:

- It could provide a good bridge to the future.
- If successful can reduce large quantities of CO_2 from the atmosphere.
- Allows continued use of fossil fuels which provides an economic advantage for some economies.
- Energy security around the world.
- Helps to clean up coal-fired power plants in developing economies that need access to energy.
- Allows emissions to be reduced without having to change lifestyles too much.

3. **Public preparation/engagement in a CCS project**

Being “aware” of CCS does not suffice in preventing public opposition to, and assuring a community’s support for a project and its engagement in it. Community input should be encouraged throughout the project from its inception and achieving it requires time and preparation. Aspects of this preparation entail “training” of community representatives, arranging (if possible) site visits to existing CCS projects and providing the community with access to technical and legal documents and expert advisors.

Experience indicates that engagement of the community in a CCS project includes informing, consulting and negotiating. All should be done prior to commencement of the project and before major decisions or actions are being taken and, most importantly, following consideration of the community’s input. The community must be engaged in all stages of the project, starting with a feasibility study, site selection for CO_2 storage (including social and environmental impact assessments), construction, operation and monitoring – all aimed at garnering the community’s informed consent (Bartlett, GCCSI).

Finally, a grievance mechanism, inclusive of all stakeholders, should be established to detect address and resolve grievances and systemic problems in the project through dialog, including recording and tracking progress.

Example of steps to community engagement:

The Asia-Pacific Economic Cooperation (APEC) - Seven steps to community engagement

The APEC Community Outreach Strategy for CO_2 Capture and Storage Projects provides a seven-step guide to engage the community in a project (APEC, 2012):

1. *Develop a team and a plan to communicate with the public about your planned CO_2 storage project*
2. *Identify and prioritize community groups relevant to the project*
3. *Define and test the interests, priorities and concerns of community groups*
4. *Prepare a communications plan, messages and materials*
5. *Deliver the messages and listen to community groups*
6. *Measure the effectiveness of the outreach*
7. *Develop a long-term communications plan with community groups*

CCS Communication Framework for Japan

Experience during engagement in Japan has shown that knowledge sharing is a critical need for the CCS community (NUS Co., 2014). The scope of knowledge sharing associated with a multidisciplinary project such as CCS, which requires consensus between various stakeholders, is two-fold:

1. Integration of experts' knowledge distributed among diverse scientific/engineering disciplines and
2. Establishing effective channels of communication between experts and non-expert stakeholders.

The main conclusions arising from the Japan experience of a CCS outreach program, are as follows.

- *The need to provide information that helps laypeople clearly understand how CO_2 is collected, transported, and stored.*
- *Science communication on global warming is a highly effective means of promoting understanding of CCS.*
- *Providing information that focuses on both kinds of risks—risks associated with the use of CCS and those without the its use—promotes participants' understanding of the necessity of CCS use.*
- *Explaining the underground storage trapping mechanism, especially through experiments, promotes understanding of CO_2 injection and long-term storage security.*
- *Experts' participation leads to effective communication, especially regarding a new technology.*
- *Continuous communication promotes mutual understanding.*

Developing the Public Engagement Strategy for the Guangdong CCUS Demonstration Program

Public support or opposition for new infrastructure projects in China is becoming an increasingly influential factor on whether or not projects are built. Therefore, a successful strategy will be needed for an intended CCS demonstration project (Ashworth et al., 2015). Based on local experience critical considerations include:

1. *Addressing the needs and interests of key stakeholders (those impacted by, and/or with influence on a project).*
2. *Finding appropriate communication tools in addition to print media, which may include online avenues and more proactive use of social media.*

3. *Ensuring that project proponents, including government and industry, act in a transparent manner that includes providing accessible and factual information.*
4. *Exerting additional efforts and creating awareness raising/educational opportunities, in order to build positive relationships and trust between stakeholders and project developers.*
5. *Identifying key communication messages which should be consistent across all parties involved in a project. Messages may include:*

- *Project goals*
- *Addressing misconceptions associated with* CO_2
- *The role that CCUS technologies can play in addressing climate change*
- *Economic and social benefits associated with the project.*

5 RESULTS

In this chapter we present preliminary assessment of CC potential during fuels production from natural gas in Israel. For all fuel substitutes, we assume the following: In 2017, 3,234 thousand metric tons (3.234 Mt) of gasoline, and 3,445 thousand metric tons (3.445 Mt) of diesel were used for transportation. Both gasoline and diesel used for transportation increases at about 3% annually (MOE, 2018). Therefore, if we assume that this rate will continue, the predicted transportation fuel use in 2030 would equal 4,398 thousand metric tons (4.398 Mt) of gasoline, and 4,685 thousand metric tons (4.685 Mt) of diesel. Together, 8,030 thousand metric tons (8.03 Mt) of transportation fuels.

Note that life cycle emission assessments account differently for upstream CH_4 emissions from natural gas systems where new data has become available in recent years (Howarth, 2014; Lavoie et al., 2017; Petrenko et al., 2017; Sanchez & Mays, 2015; Schneising et al., 2014; Worden et al., 2017).

The natural gas currently produced from the Tamar field in Israel's is fairly 'dry' (low levels of higher hydrocarbons and other impurities) and it is mostly composed of CH_4. It requires minimal treatment before transporting it to the costumers (Delek, 2015; Delek, 2016). The 'Tamar' natural gas has a low CO_2 content, which would make it irrelevant to capture carbon from the raw natural gas, while compressing it to produce CNG. If in the future, Israel will have a natural gas rich with CO_2, it would be advisable to capture and store it after separation.

5.1 CNG

According to the FCI, CNG is expected to account for 22% of Israel's transportation fuel mix in 2030 (FCI, 2016) - see Section 1.3. Since CNG production do not produce CO_2 emissions, CCS is irrelevant.

5.2 Methanol

According to the FCI, MeOH is expected to account for 10% of Israel's transportation fuel mix in 2025-2030 (FCI, 2016). **In 2030, if 10% of transportation fuels is MeOH (1.7 Mt MeOH/year), CCS\U could capture annually ~0.3 MtCO$_2$e during MeOH production, and lower natural gas**

consumption for MeOH production by 20%. All this with no additional cost, and maybe even cheaper than without CCS\U. It seems that CCU\S is a win-win situation for MeOH. The calculations are detailed in Appendix D.

Transport and storage

The additional cost for transporting and storing the 0.25-0.35 Mt CO_2e/year from MeOH production is 10-35 million ILS_{16}/year, as calculated below:

$$0.25\ to\ 0.35\ MtCO_2e/year *\ 40\ to\ 100\ ILS_{16}/tCO_2e =\ \mathbf{10\ to\ 35\ million\ ILS_{16}/year} \tag{4}$$

5.3 GTL

We are using domestic GTL data. Domestic GTL is produced from domestic natural gas, and not from foreign shipped LNG for example.

GTL is expected to account for 12% of Israel's transportation fuel mix in 2025-2030 (FCI, 2016). Therefore, in order to replace 12% of the 8.03 Mt of gasoline and diesel that are projected to be used in 2030 would require the production of 0.964 Mt GTL annually from 2030 and beyond. **In 2030, if 12% of transportation fuels is domestic GTL (0.964 Mt GTL/year), CCS could capture annually 1.63 $MtCO_2e$ during domestic GTL production**, as detailed in Appendix E.

The report titled, "Integration of Natural Gas Based Oil Replacements in Israel Transport Sector" (MOE, 2012b) calculated a scenario in which the GTL production in 2022 will be double that of the projection by the FCI for 2030 (FCI, 2016). So, while 1.9 Mt domestic GTL production will generate 9.14 $MtCO_2e$ annually, CCS could capture 3.38 $MtCO_2e$.

Costs Assessment for Israel Case Study:

Carbon capture cost:

As shown in Section 3.2, the break-even price for carbon capture is only 30.55 ILS_{16}/tCO_2e (6 EUR_{05}/tCO_2e) at a GTL plant gate (van Vliet et al., 2009). Therefore, the additional cost in a GTL plant to process the separated CO_2 before transport and storage is:

$$1.63\ MtCO_2e/year *\ 30.55\ ILS_{16}/tCO_2e =\ \mathbf{49.8\ million\ ILS_{16}/year} \tag{5}$$

For GTL constituting 24% (1.9 Mt GTL/year) of 2030 transportation fuel mix (MOE, 2012b), the additional cost for preparing CO_2 in the GTL plant is as follow:

$$3.38\, MtCO_2e/year * \ 30.55\, ILS_{16}/tCO_2e = \ \mathbf{103.3\ million\ ILS_{16}/year} \tag{6}$$

Capital cost:

In a ~5.5 million barrels/year GTL plant (16,000 barrels/day), the additional capital cost for CO_2e capture (compressing the already separated CO_2e) in a GTL plant is 91.6 million ILS_{16} (18 million EUR_{05}), which is only a 1.5% increase in the plant total capital cost. A larger plant size is not expected to reduce the cost per/barrel (van Vliet et al., 2009).

In the Israeli case, 12% GTL share of all transportation fuels in 2030, which is 0.964 Mt GTL/year, equals to[22]:

$$\frac{0.964\ Mt\ GTL/year}{0.8\ kg} = 1{,}205{,}000{,}000\ liter\ GTL/year \tag{7}$$

$$\frac{1{,}205{,}000{,}000\ liter\ GTL/year}{159\ liter/barrel} \sim \mathbf{7.5\ million\ barrels\ GTL/year} \tag{8}$$

So, in a ~7.5 million barrels/year GTL plant, the additional capital cost for CO_2e capture is still 1.5% from the total capital cost:

$$\frac{7.5\ million\ barrels/year}{5.55\ million\ barrels/year} = 1.36 \tag{9}$$

$$1.36\ *\ 91.6\ million\ ILS_{16} = \ \mathbf{124.6\ million\ ILS_{16}} \tag{10}$$

24% GTL share of all transportation fuels in 2030, equals to ~7.75 million barrels/year GTL plant:

For GTL constituting 24% (1.9 Mt GTL/year) of 2030 transportation fuel mix (MOE, 2012b), the additional capital cost for preparing CO_2 in the GTL plant is 250 million ILS_{16}.

---

[22] 1 barrel = 159 liter, 1 liter GTL~0.8 kg

Transport & storage:

Since it costs 40-100 ILS_{16}/tCO_2e to transport and store (see Chapter 3) (Collodi et al., 2017; Rubin et al., 2015), so in the 12% GTL share of all transportation fuels in 2030 scenario, transport and storage of 1.63 $MtCO_2e$ will cost 65-163 million ILS_{16}/year, as calculated below:

$$40\ to\ 100\ ILS_{16}/tCO_2e * 1.63\ MtCO_2e/year = \mathbf{65\ to\ 163\ million\ ILS_{16}/year} \qquad (11)$$

In the 24% GTL share of all transportation fuels in 2030 scenario, transport and storage of 3.38 $MtCO_2e$ will cost 130-326 million ILS_{16}/year.

5.4 Electricity

In 2016, 67 TWh of electricity was used in Israel, of which 62% was produced using natural gas. By the end of 2018 more than 70% will be produced using natural gas, with a plan to end the use of coal by 2030.

Electricity demand in 2030, is expected to be 90-95 TWh/year (Gal, Paltar, Rabi, & Kiro, 2017). It is predicted that 80-90% of the electricity in 2030 will be produced by natural gas (with the rest by renewables) (PR, 2018a; PR, 2018b), hence, 72-86 TWh will be produced by natural gas.

1 MWh electricity from combined cycle natural gas turbines emits 0.36 tCO_2e/MWh[23] (Rubin et al., 2015), therefore, CO_2e emissions from electricity produced by natural gas is expected to be 26-31 $MtCO_2e$/year, as calculated below:

$$72\ to\ 86 * 10^6\ MWh * 0.36\ tCO_2e/MWh = \mathbf{26\ to\ 31\ MtCO_2e/year} \qquad (12)$$

Out of this, CCS can capture ~90% of the carbon = 23.3-27.9 $MtCO_2e$/year.

So, CCS can capture 23.3-27.9 $MtCO_2e$/year from natural gas-based electricity production in 2030. This is a substantial amount of CO_2e, equals to 25-30% of Israel's GHGs emission estimation for 2030 (Proactor, Cohen-Ginat, Rozen, Weinstein, & Elul, 2016). Note that this amount is for capturing 72-81% CO_2e emissions of **all** electricity production, and not only for EVs.

If 20% of all transportation fuels will be electric in 2030 (FCI, 2016), it will use 6% of all electricity, with 5 TWh/year. Electric trains will use 1.2 TWh/year in 2030 (Hertzog et al., 2016), which together

---

[23] Currently, the CO_2e emission factor in Israel 2017 is 0.45 tCO_2e/MWh. The theoretical factor of 0.36 tCO_2e/MWh will be met by further improvements.

amount to 6.2 TWh/year. Thus, the relative portion of CO_2e emissions from electricity production that CCS can capture for EVs is 1.6-1.8 $MtCO_2e$/year. The calculations are detailed in the text box below:

---

*6.2 TWh/year * 0.36 tCO_2e/MWh = 2.23 $MtCO_2e$/year emissions for electric transportation.*

*80% to 90% of electricity is from natural gas * 2.23 $MtCO_2e$/year = 1.8 to 2 $MtCO_2e$/year is from natural gas.*

*90% of CO_2 emissions can be captured * 1.8 to 2 $MtCO_2e$/year = 1.6 to 1.8 $MtCO_2e$/year.*

An updated report predicts only ~10% electric transportation of all transportation in 2030. Electric cars will use 3% of all electricity, with 2.5 TWh/year, while electric trains will use 1.2 TWh/year in 2030. The total electricity use by transportation will be 3.7 TWh/year - 4.45% of all electricity (Hertzog et al., 2016). Therefore, the portion of potential CCS for the electric transportation portion in this scenario is 1-1.1 $MtCO_2e$/year.

Capture cost

In the scenario of 20% electric transportation in 2030, CO_2e capture cost of the electric transportation portion is 448-1,026 million ILS_{16} /year, as calculated below:

$$1.6-1.8\ MtCO_2e/year * \ 280-570\, ILS_{16}/tCO_2e = \mathbf{448-1{,}026\ million\, ILS_{16}/year} \tag{13}$$

For all electricity, in 2030, CO_2e capture cost of the electric transportation portion is 6,524-15,903 million ILS_{16} /year:

$$23.3-27.9\ MtCO_2e/year * \ 280-570\, ILS_{16}/tCO_2e = \mathbf{6{,}524-15{,}903\ million\, ILS_{16}/year} \tag{14}$$

In the scenario of 10% electric transportation in 2030 (Hertzog et al., 2016), CO_2e capture cost of the electric transportation portion is 280-575 million ILS_{16} /year.

Transport & storage cost

In the scenario of 20% electric transportation in 2030, the cost of transporting and storing 1.6-1.8 $MtCO_2e$/year is 64-180 million ILS_{16}/year, as calculated below:

$$1.6 - 1.8\ MtCO_2e/year * 40 - 100\, ILS_{16}/tCO_2e = \mathbf{64 - 180\, million\, ILS_{16}/year} \qquad (15)$$

In the scenario of 10% electric transportation in 2030, the cost of transporting and storing 1-1.1 $MtCO_2e$/year is 40-100 million ILS_{16}/year.

For all of the electricity sector, the cost of transporting and storing 23.3-27.9 $MtCO_2e$/year is 932-2,790 million ILS_{16}/year, as calculated below:

$$23.3 - 27.9\ MtCO_2e/year * 40 - 100\, ILS_{16}/tCO_2e = \mathbf{932 - 2,790\, million\, ILS_{16}/year} \qquad (16)$$

5.5 CO_2 storage in Israel

The geological survey of Israel[24], has conducted a substantial amount of research regarding CO_2 storage in deep saline aquifers. They studied seismic, drilling and simulations data.

Among others, the studies calculated that it is possible to store 4,000 $MtCO_2$ in seven distinct stratigraphic units in the Negev (Calvo, 2014; Calvo, Rosenzweig, Bar, Buch-Leviatan, & Gvirtzman, 2014). This amount is equal for all of Israel's CO_2 emissions for ~50 years. Alternatively, these deep saline aquifers could receive 20% of Israel's annual CO_2 emissions for ~250 years (Proactor et al., 2016). Another study calculated that in 230 years after the beginning of CO_2 injection into the Jurassic saline aquifers, only 0.15% of the injected CO_2 is expected to leak (Rosenzweig, Cohen, & Holtzman, 2016).

These studies suggest that Israel has a sufficient deep saline aquifer storage potential for decades and centuries to come.

5.6 Results summary

CCS in raw natural gas processing is so far irrelevant in Israel, as our natural gas has a very low fraction of CO_2. CCS is also irrelevant to CNG production.

CCU\S in a MeOH plant is highly cost-effective and might be profitable. CCS in a GTL plant is also very cost-effective, as most of the investment is required with or without CCS. But, implementing CCS in these facilities can reduce out GHGs emissions by only 2-4 $MtCO_2e$/year (see Table 5-1,

---

[24] The Geological Survey of Israel - http://www.gsi.gov.il/?CategoryID=572

Figure 5-1 and Figure 5-2), which will be less than 2-4% of our annual GHGs emissions in 2030 (Proactor et al., 2016).

Per tCO_2e, CCS in power plants is the most expensive, and requires CCS for the whole power plant and not only for the fraction of electricity produced for electric transportation. However, it also has the only real potential to significantly reduce Israel's GHGs emissions. It can reduce 25-30% of Israel's GHGs emission estimation for 2030 (Proactor et al., 2016).

Combining all the fuel substitutes together, we calculated that the potential for CCS from the fuel substitutes sector is 2.9-5.5 $MtCO_2e$/year (see Table 5-1, Figure 5-1 and Figure 5-2). **The overall cost (capture, transport, storage) is 445-1,670 million ILS_{16}/year. Israel's deep saline aquifers can receive this amount of annual CO_2 for ~800 years.**

When all of the CCS in natural gas power plants is included we can capture 24.9-30.7 $MtCO_2e$/year. The overall cost (capture, transport, storage) is 7,581-19,157 million ILS_{16}/year (see Table 5-1, Figure 5-1 and Figure 5-2).

Note that these costs are expected to be lower, as all the technologies mature overtime (Chapman et al., 2013). Israel's deep saline aquifers can receive this annual CO_2 amount for ~130 years.

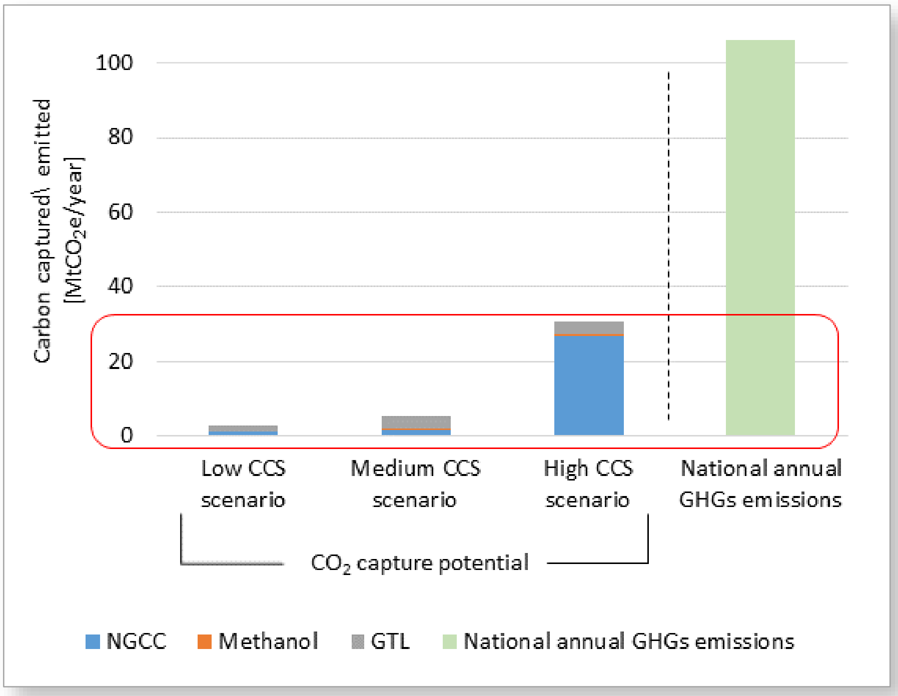


Figure 5-1 > Cumulative potential for CCS in natural gas-based transportation fuel substitute's facilities

The right bar in Figure 5-1 is the annual GHGs national emissions in 2030, and the three left bars are CO_2 capture potentials in three scenarios (see Table 5-1):

- Low CCS implementation (1 $MtCO_2e$/year from NGCC, 0.25 $MtCO_2e$/year from methanol, 1.63 $MtCO_2e$/year from GTL);
- Medium CCS implementation (1.8 $MtCO_2e$/year from NGCC, 0.35 $MtCO_2e$/year from methanol, 3.38 $MtCO_2e$/year from GTL);
- High CCS implementation (27 $MtCO_2e$/year from NGCC, 0.35 $MtCO_2e$/year from methanol, 3.38 $MtCO_2e$/year from GTL).

The red rectangle in Figure 5-1 is enlarged in Figure 5-2.

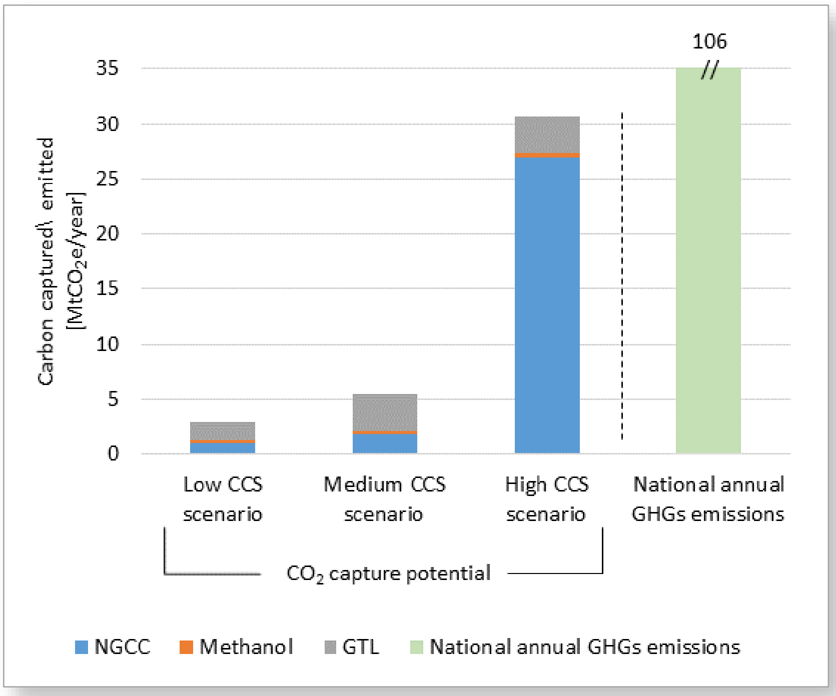


Figure 5-2 > Enlargement of Figure 5-1 lower values of cumulative potential for CCS in natural gas-based transportation fuel substitute's facilities

Table 5-1 > CCS potential from the transportation fuel substitutes sector

Fuel substitute	Portion in 2030 transportation fuels sector	Potential CO_2e capture $MtCO_2e$/year	Capture cost ILS_{16}/tCO_2e	Capture cost in million ILS_{16}/year	Transport & storage cost in million ILS_{16}/year	Capture, transport & storage cost in million ILS_{16}/year
CNG	22% [a]	-		-	-	-
Methanol	10% [a]	0.25-0.35 (It also reduces natural gas consumption for MeOH production by 20%)	Might be profitable	Might be profitable	10-35	10-35 (Might break even or be profitable)
GTL	12% [a]	1.63	30	50	65-163	115-213
GTL	24% [b]	3.38	30	103	130-326	233-426
Electricity	20% [a]	1.6-1.8	280-570	448-1,026	64-180	512-1,206
Electricity	10% [c]	1-1.1	280-570	280-575	40-100	320-675
Electricity	CCS of all electricity sector [d]	23-27 [d]	280-570	6,524-15,903	932-2,790	7,456-18,693
Total	**54-76%**	**2.9-5.5**	**-**	**330-1129**	**115-541**	**445-1,670**
Total (including all electricity sector)		(24.9-30.7)	-	(6,574-16,006)	(1,007-3,151)	(7,581-19,157)

All transportation cost is calculated for onshore 150 km pipeline. All storage cost is calculated for storing in deep saline formations in the Northern Negev. It costs 40-100 ILS_{16}/tCO_2 to transport and store, see Chapter 3 (Collodi et al., 2017; Rubin et al., 2015). Note that costs are expected to be lower, since technologies mature overtime.

---

[a] According to (FCI, 2016).

[b] According to (MOE, 2012b).

[c] According to (Hertzog et al., 2016).

[d] The total amount of potential CO_2e capture from all electricity production.

6 KEY FINDINGS AND RECOMMENDATIONS

Key Research Findings

As indicated in Section 1.2, the last IPCC report concluded that without implementation of CCS technologies, the cost of achieving atmospheric concentrations of 450 ppm CO_2e by 2100 could be 138% more costly, as compared to scenarios that include CCS. There are only a minority of climate model runs that successfully produce a 450 ppm scenario in the absence of CCS (IPCC, 2014). The models take into account 10-15% reduction in GHGs emissions using CCS.

The data compiled in this study has implications for potential implementation in Israel:

Raw natural gas processing:
CCS in Israel is presently irrelevant for raw natural gas processing, as the raw natural gas presently extracted in Israel is poor in CO_2.

CNG production:
CCS is irrelevant for CNG production, as its production does not emit CO_2.

Methanol plant:
Adding CCS to a MeOH plant may reduce CO_2e emissions by 11% if the carbon in the process is captured and stored. This can at the same time boost MeOH production by 20%, while lowering process energy demand by 5%, and natural gas consumption by 16%. The captured CO_2 can be transported and stored in a deep saline aquifer or other suitable formation.
With incentives for MeOH CCS, transporting and storing the captured CO_2 can be achieved without any net cost. It is expected that 0.25-0.35 $MtCO_2$ could be captured, transported and stored annually at a cost of 10-35 million ILS_{16}, or even without any net cost. This is due to the fact that most of the infrastructure needed to CO_2 capture will already be available in the MeOH plant regardless of CCS\U. Also, CCU in MeOH plants can increase MeOH production while reducing natural gas and energy consumption (see Sections 3.2 and 5.2 on methanol, and the summary of Chapter 5).

GTL plant:
For a GTL plant the data suggests that it is possible to reduce 37% of CO_2e emissions from the GTL life-cycle by applying CCS. Implementation of CCS technologies, including transport and storage, can be achieved at a relatively low cost, since most of the CO_2 capture process is already an integral

part of the GTL conversion process. The CO_2e capture cost for a GTL facility is 10 times lower than for a NGCC power plant, due to the fact that most of the CO_2 capture infrastructure is already part of the GTL plant regardless of whether the full CCS process is implemented or not. It is expected that 1.63-3.38 $MtCO_2e$ could be captured, transported and stored annually at a cost of 115-426 million ILS_{16}. This will lead for only a 3.5% increase in the fuel production cost (see Sections 3.2 and 5.3 on GTL, and the summary of Chapter 5).

Even though the results for MeOH and GTL look promising, together they comprise a reduction of 2-4 $MtCO_2e$ annually, which is less than 2-4% of Israel's expected 2030 annual GHGs emissions.

Natural gas power plants:

CCS in NGCC power plants can reduce 65% of the life-cycle GHGs emissions of electricity production. Installation of CCS in power plants to cover the expected incremental electricity generation for the expected share of electric transportation in 2030, may require capturing, transporting and storing 1-1.8 $MtCO_2e$ annually at a cost of 320-1,206 million ILS_{16} (see Sections 3.2 and 5.4 on electricity, and the summary of Chapter 5).

Combined implementation of CCS in the natural gas fuel substitutes sector:

Combining the three fuel substitutes (MeOH blend, GTL and EVs) may require capturing, transporting and storing 2.9-5.5 $MtCO_2e$ annually at a cost of 445-1,670 million ILS_{16} (see Section 3.2 and Chapter 5). Altogether, this amounts to 15-37% of the transportation sector expected GHGs emissions in 2030. This can be a fair amount of GHGs reduction for the transportation sector. However, this amounts to less than about 3-6 % of Israel's expected 2030 annual **national** GHGs emissions.

For a substantial reduction of CO_2 emissions using CCS, there would be a need to implement CCS in most power plants. Then, it is possible to capture, transport and store 24.9-30.7 $MtCO_2e$ annually from MeOH, GTL and electricity. However, this would come at a very high annual cost of 7,581-19,157 million ILS_{16}, due to the high power plant capture cost (see summary of Chapter 5).

If MeOH and\or GTL plants will be constructed as part of Israel’s FCI, it will probably be undertaken regardless of whether CCS or CCU will be implemented. It is expected that constructing and operating such plants will have substantial environmental impacts in addition to their impact on GHG emissions. Since implementing CCS or CCU in these specific cases are expected to have very limited incremental environmental impact, adding them to the plants may help to reduce their environmental impact and could have environmental benefits (see Section 4.2). On the other hand, although adding CCS to power plants might reduce GHG emissions, it could have other significant environmental impacts.

CO_2 storage:

Seven deep saline aquifers in southern Israel can receive the above-mentioned amount of annual CO_2 for 130-800 years. Out of all CO_2 injected to the ground, only 0.15% is expected to escape in the 230 years following injection start. This is the most suitable storage option for Israel today, and there is more than enough storage capacity for our needs.

Key Policy Findings

The findings about the presence of large-scale projects in countries such as the US, Canada, Australia and China indicate that large-scale CCS deployment requires:

1. A moderate to high dependence on fossil fuel production/consumption and a genuine desire by the government to address growing emissions from these sources;
2. Supportive national and regional policies to back this overall desire, including direct or indirect financing mechanisms, including economic incentives to promote energy efficiency, renewable energy and incentivizing construction of CCS plants. Negative incentives can include carbon tax;
3. Legal and regulatory frameworks to ensure all components of the CCS technology chain are addressed; and
4. A portfolio of storage sites which have been identified, with early opportunities appraised and developed.

In addition, it can be noted that nations with high regulatory readiness for CCS deployment have developed their CCS industry over at least two decades. This has included the development of policy commitments, legislative development, and storage characterization, as well as industry engagement and applied research.

Therefore, unique challenges for CCS deployment include:

- Predictability in policy setting is paramount,
- Need for multi-industry focus,
- Commercial integration across all three elements of the CCS chain,
- Early identification and characterization of suitable geological storage sites,
- Legal and regulatory regimes that provide clear obligations and liability provisions,

- Robustness in R&D efforts,
- Increasing community awareness of the importance of CCS.

As discussed in Section 4.3 above, for CCS to be implemented on the scale necessary to affect GHG emissions, efforts are needed to inform and raise awareness among the general public about CCS. The public needs to know what exactly CCS is, how it works and what are its pros and cons. Broad public awareness of CCS' effectiveness will help alleviate concerns, promote positive opinions and encourage the engagement of the communities where CCS projects are planned to be undertaken.

Policy Recommendations

The survey conducted here reinforces elements of the policy-making process that are critical to enabling and/or accelerating the deployment of CCS. These include:

- Government tracking and verification of adhering to the economy-wide emissions reduction targets, consistent with the aims of the Paris Agreement.
- Designing policy to achieve medium-term emissions reduction in a range of sectors and in line with these longer-term targets.
- Explicitly including CCS in national climate action plans or similar flagship policy statements, which either implicitly or explicitly acknowledge how CCS can play a role alongside other low carbon technologies.
- Securing policy certainty via a government commitment that has been demonstrated to extend beyond political cycles and to be resilient to conflicting political demands.
- Establishing public/private engagement to address the risk between the capture, transport and storage elements of the CCS chain, thus reducing overall risks.
- Devoting special attention to accelerating investment in storage exploration and characterization, in view of the long lead times for development of such locations.
- Including economic incentives to promote energy efficiency, renewable energy and incentivizing construction of CCS plants. Negative incentives can include carbon tax.

Research limitations

This is a limited review of CCS. We have reviewed the CCS field and presented **preliminary** results for implementation of CCS in Israel. We did not conduct a techno-economic analysis for CCS in Israel. We did not conduct a full environmental analysis for implementing CCS in Israel.

Also, Israel has specific conditions not present in other countries that favor uncommon CCS solutions, such as the plans to build MeOH and GTL facilities for transportation fuel substitutes. Uncommon CCS solutions attract less research. Therefore, the conclusions on these uncommon CCS solutions are less robust and might be less accurate.

Recommendations for the Ministry activity and for implementing the results of the research in Israel

Since most of the CO_2 capturing facilities are part of MeOH and GTL plants regardless of CCS implementation, and MeOH and GTL plants are expected to have significant environmental impacts, if MeOH and\or GTL plants will be constructed as part of the FCI, it is recommended to stipulate such construction with the implementation of CCS\CCU in these facilities. Moreover, it is recommended to develop transport and storage facilities for the captured CO_2. Without certainty in transporting and storing CO_2, as indicated in the Policy Recommendations above, merely capturing the CO_2 is useless. This might be achieved at no net cost in a MeOH plant, and at a proportionally very small increase in cost in a GTL plant.

Recommendations for further research

Due to the fact that this is a limited review, this field could not be studied thoroughly. Especially, implementing CCS in Israel. We recommend on the following necessary research in the field:

- A techno-economic analysis of implementing CCS in Israel.
- An environmental assessment of implementing CCS in Israel, especially in power plants.
- Specific research in implementing CCS\U in MeOH facilities.
- Specific research in implementing CCS in GTL facilities.
- A comparison of different low carbon energy solutions for Israel: renewables and energy storage, CCS, nuclear energy.
- Pursue novel CCU solutions that will allow lowering CCS\U capture cost.
- More CO_2 storage in Israeli deep saline formations.

7 REFERENCES

APEC (2012). "Increasing the Knowledge and Awareness of Carbon Capture and Storage: Capacity-Building in the APEC Region", APEC Energy Working Group Project EWG 05/2010A Prepared by ICF International, September 2012

Aradóttir, E. S., Sigurdardóttir, H., Sigfússon, B., Gunnlaugsson, E. (2011). "CarbFix: a CCS pilot project imitating and accelerating natural CO_2 sequestration of Greenhouse Gases", *Sci. Technol. 1*(2):105–18, 2011.

Arienti, S., Cotone, P., Mancuso, L., & Valota, L. (2008). *Co-production of hydrogen and electricity by coal gasification with CO_2 capture - 5.4 Capital Costs, 5.5 Operating Costs & Option Selection*. Milano. Retrieved from https://hub.globalccsinstitute.com/publications/co-production-hydrogen-and-electricity-coal-gasification-co$_2$-capture-updated-economic-analysis/54-capital-costs

Ashworth, P., Mayhew, M., Millar, F. And Boughen, N., (2007). "An integrated roadmap of Communication Activities around Carbon Capture and Storage (CCS) in Australia and Beyond", cLET/CSIRO report P2007/975, October 2007.

Ashworth, P., Boughena, N., Mayhewa, M., Millara, F. (2009). "An integrated roadmap of communication activities around carbon capture and storage in Australia and beyond", *Energy Procedia, 1:* 4749–4756

Ashworth, P., Mortong, J., Yamin Lin, Si Cao, Xi Liang, (2015). "Developing the Public Engagement Strategy for the Guangdong CCUS Demonstration Program", UK-China (Guangdong) CCUS Center, September 2015

Bartlett, A., GCCSI. "Module 13 Public awareness and community consultation", Global CCS Institute. https://hub.globalccsinstitute.com/publications/building-capacity-co$_2$-capture-and-storage-apec-region-training-manual-policy-makers-and-practitioners/module-13-public-awareness-and-community-consultation

Benson, S.M., Bennaceur, K., Cook, P., Davison, J., de Coninck, H.C. (2012). "Carbon dioxide capture and storage". In *Global Energy Assessment: Toward a Sustainable Future*, ed. L Gomez-Echeverri, TB Johansson, N Nakicenovic, A Patwardhan, pp. 993–1068, 2013, Cambridge, UK/New York: Cambridge Univ. Press

Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., … Fennell, P. S. (2014). Carbon capture and storage update. *Energy Environ. Sci.*, *7*(1), 130–189. https://doi.org/10.1039/C3EE42350F

Byers, E. A., Hall, J. W., Amezaga, J. M., O'Donnell, G. M., & Leathard, A. (2016). Water and climate risks to power generation with carbon capture and storage. *Environmental Research Letters*, *11*(2), 24011. https://doi.org/10.1088/1748-9326/11/2/024011

Calvo, R. (2014). *A comparative study for potential CO_2 storage units in the subsurface Paleozoic-Mesozoic section in Southern Israel- Arad Group- Middle Aquifer and Middle Aquitard*. Jerusalem. Retrieved from http://www.gsi.gov.il/_uploads/ftp/GsiReport/2014/Ran-(Calvo)-GSI-25-2014.pdf

Calvo, R., Rosenzweig, R., Bar, O., Buch-Leviatan, O., & Gvirtzman, Z. (2014). *Examination of CO_2 storage scenarios in the middle saline aquifer (Ardon, Inmar, Daya, Sherif and Zohar formations) of the Northern Negev*. Jerusalem. https://doi.org/The Geological Survey of Israel

Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., … Miller, B. R. (2014). Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences*, *111*(17), 6237–6242. https://doi.org/10.1073/pnas.1316546111

CBS (2018). *Energy.* Retrieved from Central Bureau of Statistics: http://cbs.gov.il/reader/?MIval=cw_usr_view_SHTML&ID=561

Chapman, J., Baker, A., Rennie, A., Stringer, T., Donaldson, I., Golder, J., … Farley, M. (2013). *The potential for reducing the costs of CCS in the UK - Final Report*. London. Retrieved from https://www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report

Collodi, G., Azzaro, G., Ferrari, N., & Santos, S. (2017). Demonstrating Large Scale Industrial CCS through CCU – A Case Study for Methanol Production. *Energy Procedia*, *114*, 122–138. https://doi.org/10.1016/j.egypro.2017.03.1155

Consoli, C. P., Havercroft, I., & Irlam, L. (2017). Carbon capture and storage readiness index: comparative review of global progress towards wide-scale deployment. *Energy Procedia*, *114*, 7348-7355.

Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of* CO_2 *Utilization*, *9*, 82–102. https://doi.org/10.1016/J.JCOU.2014.12.001

Davidson, C. L., Dahowski, R. T., McJeon, H. C., Clarke, L. E., Iyer, G. C., & Muratori, M. (2017). The value of CCS under *current* policy scenarios: NDCs and beyond. *Energy Procedia*, *114*, 7521-7527.

Davies, L. L., Uchitel, K., & Ruple, J. (2013). Understanding barriers to commercial-scale carbon capture and sequestration in the United States: An empirical assessment. *Energy Policy*, *59*, 745-761.

de Coninck, H., & Benson, S. M. (2014). Carbon Dioxide Capture and Storage: Issues and Prospects. *Annual Review of Environment and Resources*, *39*(1), 243–270. https://doi.org/10.1146/annurev-environ-032112-095222

Delek (2015). *Delek Analyst 2015*. Retrieved from http://www.delekdrilling.co.il/sites/default/files/media/document/field_pt_pdf/Delek Analyst PPT Oct 2015.pdf

Delek (2016). *Delek Drilling- Anual Report 2016*. Retrieved from http://www.delekdrilling.co.il/sites/default/files/media/document/field_rp_pdf/ דלק קידוחים- שנתי 2016.pdf

EEA (2011). European Environment Agency “Air pollution impacts from carbon capture and storage (CCS)”, EEA Technical report No 14/2011.

FCI (2016). Fuel Choices Initiative - The Fuel Choices Initiative Brochure 2016. http://www.fuelchoicesinitiative.com/wp-content/uploads/2016/07/Fuel_choices_initiative-WEB-2016.pdf

Finkenrath, M. (2011). *Cost and Performance of Carbon Dioxide Capture from Power Generation* (No. 2011/05). Paris. https://doi.org/10.1787/5kgggn8wk05l-en

Folger, P. (2013). “Carbon Capture: A Technology Assessment” Congressional Research Service 7-5700, November 5, 2013; https://fas.org/sgp/crs/misc/R41325.pdf

Futurism (2018). Capturing Carbon – Act now or forever hold your peace. https://futurism.com/images/can-we-come-back-from-climate-changes-brink/

Gal, N., Paltar, N., Rabi, R., & Kiro, R. (2017). *The Israeli Electriciy Sector Status 2016*. Jerusalem. Retrieved from https://pua.gov.il/publications/documents/meshek_atatus_2016.pdf

GCCSI (2015a). "Carbon capture and storage Policy Indicator (CCS-PI) 2015 update".

GCCSI (2015b). “Global Status of CCS: 2015,”.

GCCSI (2016). “CARBON CAPTURE AND STORAGE READINESS INDEX - A global comparative analysis of CCS indicators for the widescale deployment of carbon capture and storage projects”.

GCCSI (2017). "The Global Status of CCS: 2017", Australia.

Gough, C., Mander, S., & Haszeldine, S. (2010). A roadmap for carbon capture and storage in the UK. *International Journal of Greenhouse Gas Control*, *4*(1), 1-12.

Gutman, L. (2017). Calacalist. דלק תייבא בנזין מחו"ל, בזן תצמצם יבוא לכסות על ההפסד. Retrieved from https://www.calcalist.co.il/local/articles/0,7340,L-3727753,00.html

Gutman, L. (2018). Calacalist. שטייניץ: משנת 2030 ייאסר יבוא מכוניות בנזין ודיזל. Retrieved from https://www.calcalist.co.il/conference/articles/0,7340,L-3732826,00.html

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., … Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6277–82. https://doi.org/10.1073/pnas.1312753111

Hertzog, H., Schwinkelstein, Y., Peres, E., Almog, T. (2016). *Electricity demant prediction 2017-2030 (Israel)*. Retrieved from http://www.tashtiot.co.il/wp-content/uploads/2016/11/תחזית-הביקוש-לחשמל-BDO.pdf

Hornbach, M. J., DeShon, H. R., Ellsworth, W. L., Stump, B. W., Hayward, C., Frohlich, C., … Luetgert, J. H. (2015). Causal factors for seismicity near Azle, Texas. *Nature Communications*, *6*(1), 6728. https://doi.org/10.1038/ncomms7728

Howarth, R. W. (2014). A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Science & Engineering*, *2*(2), 47–60. https://doi.org/10.1002/ese3.35

IEA (2012). "A Policy Strategy for Carbon Capture and Storage – Information paper" OECD/IEA, Paris, France.

IEA (2013). *Technology Roadmap: Carbon capture and storage*, OECD/IEA, Paris, France, 2013

IEA (2014). *CCS 2014 – What lies in store for CCS?* OECD/IEA, Paris.

IEA (2015a). *Carbon Capture and Storage: The solution for deep emissions reductions*, OECD/IEA, Paris; https://www.iea.org/publications/freepublications/publication/CarbonCaptureandStorageThesolutionfordeepemissionsreductions.pdf

IEA (2015b). *Energy Technology Perspectives 2015*: Mobilising Innovation to Accelerate Climate Action, OECD/IEA, Paris; http://www.iea.org/publications/freepublications/publication/energy-technology-perspectives-2015.html

IEA (2016a). *20 years of Carbon Capture and Storage, Accelerating future deployment*, OECD/IEA, Paris. https://www.iea.org/publications/freepublications/publication/20YearsofCarbonCaptureandStorage_WEB.pdf

IEA (2016b). *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems.* OECD/IEA, Paris.

IEA & UNIDO (2011). "*Technology* Roadmap Carbon Capture and Storage in Industrial Applications". IEA, Paris, France.

IEAGHG (2004). *Ship* Transport *of CO_2 - Carbon Capture and Storage*. (2004). Retrieved from http://www.ieaghg.org/docs/General_Docs/Reports/PH4-30 Ship Transport.pdf

IL-CBS (2015). Israeli Bureau of Statistics, Emissions from Fuel Combustion by type of consume, Table 27.6, published September 2015, Jerusalem, Israel; http://www.cbs.gov.il/shnaton66/st27_06.pdf

Im, D., Roh, K., Kim, J., Eom, Y., & Lee, J. H. (2015). Economic assessment and optimization of the Selexol process with novel additives. *International Journal of Greenhouse Gas Control*, *42*, 109–116. https://doi.org/10.1016/J.IJGGC.2015.08.001

IPCC (2005). *Special Report on Carbon Dioxide Capture and Storage*, Prepared by Working Group III of the Intergovernmental Panel on Climate Change, [Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.)]. Cambridge University Press, UK. pp 431. https://www.ipcc.ch/report/srccs/

IPCC (2014). *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, *Geneva*, Switzerland, 151 pp. http://ipcc.ch/report/ar5/syr/

IPIECA (2018). Making CCS fly. IPIECA workshop summary. http://www.ipieca.org/news/making-ccs-fly-ipieca-workshop-summary/

Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2008). Comparative Analysis of the Production Costs and Life-Cycle GHG Emissions of FT Liquid Fuels from Coal and Natural Gas. *Environmental Science & Technology*, *42*(20), 7559–7565. https://doi.org/10.1021/es8002074

Jaramillo, P., Samaras, C., Wakeley, H., & Meisterling, K. (2009). Greenhouse gas implications of using coal for transportation: Life cycle assessment of coal-to-liquids, plug-in hybrids, and hydrogen pathways. *Energy Policy*, *37*(7), 2689–2695. https://doi.org/10.1016/J.ENPOL.2009.03.001

Keranen, K. M., Savage, H. M., Abers, G. A., & Cochran, E. S. (2013). Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. *Geology*, *41*(6), 699–702. https://doi.org/10.1130/G34045.1

Lavoie, T. N., Shepson, P. B., Gore, C. A., Stirm, B. H., Kaeser, R., Wulle, B., … Rudek, J. (2017). Assessing the Methane Emissions from Natural Gas-Fired Power Plants and Oil Refineries. *Environmental Science & Technology*, *51*(6), 3373–3381. https://doi.org/10.1021/acs.est.6b05531

Llamas, B., Navarrete, B., Vega, F., Rodriguez, E., Mazadiego, L. F., Cámara, A., Otero, P. (2016). Greenhouse Gas Emissions – Carbon Capture, Storage and Utilisation, Greenhouse Gases, Dr. Bernardo Llamas (Ed.), InTech, DOI: 10.5772/63154. Available from: https://www.intechopen.com/books/greenhouse-gases/greenhouse-gas-emissions-carbon-capture-storage-and-utilisation

L'Orange Seigo, S., Dohle, S. & Siegrist, M. (2014). "Public perception of carbon capture and storage (CCS): A review", *Renewable and Sustainable Energy Reviews 38:* 848–863

Mc Grail, B.P., Schaef, H.T., Ho, A.M., Chien. Y.J., Dooley, J.J., Davidson, C.L. (2016). "Potential for carbon dioxide sequestration in flood basalts", *J. Geophysical Research*, 111: B 12201 64, 2006.

McGarr, A. (2014). Maximum magnitude earthquakes induced by fluid injection. *Journal of Geophysical Research: Solid Earth*, *119*(2), 1008–1019. https://doi.org/10.1002/2013JB010597

MOE (2012a). The Natural Gas Sector in Israel. http://archive.energy.gov.il/English/Subjects/Natural%20Gas/Pages/GxmsMniNGEconomy.aspx

MOE (2012b). Ministry of Energy - Integration of Natural Gas Based Oil Replacements in Israel Transport Sector. Economic Model and Complementary Qualitative Analysis For: CNG, Methanol & GTL. Retrieved from http://archive.energy.gov.il/Subjects/EGOilReplacement/Pages/GxmsMniORIntegration.aspx

MOE (2018). Ministry of Energy - *משק הדלק בישראל*. Retrieved from gov.il: https://www.gov.il/he/Departments/Guides/fuel_market?chapterIndex=5

MOEP (2015). *Assessment of Greenhouse Gas Emission Reduction Potential & Recommended National Target for Israel*, Ministry of Environmental Protection, Jerusalem, Israel, September 2015; http://www.sviva.gov.il/infoservices/reservoirinfo/doclib2/publications/p0801-p0900/p0823-a.pdf

Muratori, M., Kheshgi, H., Mignone, B., Clarke, L., McJeon, H., & Edmonds, J. (2017a). Carbon capture and storage across fuels and sectors in energy system transformation pathways. *International Journal of Greenhouse Gas Control*, *57*, 34–41. https://doi.org/10.1016/j.ijggc.2016.11.026

Muratori, M., Kheshgi, H., Mignone, B., McJeon, H., & Clarke, L. (2017b). The future role of CCS in electricity and liquid fuel supply. *Energy Procedia*, *114*, 7606-7614.

Noothout, P., Wiersma, F., Hurtado, O., Roelofsen, P., & Macdonald, D. (2013). *CO_2 Pipeline Infrastructure*. Cheltenham, UK. Retrieved from http://www.ieaghg.org/docs/General_Docs/Reports/2013-18.pdf

NUS Co., (2014). “Development of a CCS Communications Framework for Japan”, Japan NUS Co., Ltd. June 2014

Oelkers, E.H., Sigurdur, R., Matter, J. (2008). “Mineral carbonation of CO_2.” *Elements 4*(5):333–37 65.

Onyebuchi, V. E., Kolios, A., Hanak, D. P., Biliyok, C., & Manovic, V. (2018). A systematic review of key challenges of CO_2 transport via pipelines. *Renewable and Sustainable Energy Reviews*, *81*, 2563–2583. https://doi.org/10.1016/J.RSER.2017.06.064

Ou, X., Zhang, X. X., Zhang, X. X., & Zhang, Q. (2013). Life Cycle GHG of NG-Based Fuel and Electric Vehicle in China. *Energies*, *6*(5), 2644–2662. https://doi.org/10.3390/en6052644

Petrenko, V. V., Smith, A. M., Schaefer, H., Riedel, K., Brook, E., Baggenstos, D., … Severinghaus, J. P. (2017). Minimal geological methane emissions during the Younger Dryas–Preboreal abrupt warming event. *Nature*, *548*(7668), 443–446. https://doi.org/10.1038/nature23316

Pietzner, K., Schumann, D., Tvedt, S. D., Torvatn, H. Y., Næss, R., Reiner, D. M., ... & Dudu, A. (2011). Public awareness and perceptions of carbon dioxide capture and storage (CCS): Insights from surveys administered to representative samples in six European countries. *Energy Procedia*, *4*, 6300-6306.

PMO (2013). Prime Minister's Office - Government decision 5327: reducing Israeli dependency on oil in transportation. Retrieved from http://www.pmo.gov.il/Secretary/GovDecisions/2013/Pages/des5327.aspx

PR (2018a). Press release- Completion of a strategic-environmental project to reduce air pollution from the Orot Rabin facility. (2018). Retrieved February 18, 2018, from https://www.gov.il/he/Departments/news/orot_rabin

PR (2018b). Press release- Reduction of 30% in the use of coal for electricity production. (2018). Retrieved February 18, 2018, from http://www.sviva.gov.il/InfoServices/NewsAndEvents/MessageDoverAndNews/Pages/2018/01-Jan/30percent-reduction-use-coal-electricity-generation.aspx

Proactor, G., Cohen-Ginat, R., Rozen, A., Weinstein, E., & Elul, N. (2016). *Israeli national plan to realize the Paris climate agreement*. Jerusalem. Retrieved from http://www.sviva.gov.il/infoservices/reservoirinfo/doclib2/publications/p0801-p0900/p0836.pdf

Raleigh, C. B., Healy, J. H., & Bredehoeft, J. D. (1976). An experiment in earthquake control at rangely, colorado. *Science (New York, N.Y.)*, *191*(4233), 1230–7. https://doi.org/10.1126/science.191.4233.1230

Rao, A. B., & Rubin, E. S. (2002). A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control. *Environmental science & technology*, *36*(20), 4467-4475.

Rosenzweig, R., Cohen, E., & Holtzman, R. (2016). *Modeling CO_2 migration and trapping in the Jurassic saline aquifers of the Negev-final report- GSI/32/2016*. Jerusalem. Retrieved from http://www.gsi.gov.il/_uploads/ftp/GsiReport/2016/Rosenzweig-R-Modeling-CO_2-Migration-Trapping-Jurassic-Saline-GSI-32-2016.pdf

Rubin, E.S. (2010). Will Carbon Capture and Storage Be Available in Time? American Association for the Advancement of Science 2010 Annual Meeting. San Diego, CA.

Rubin, E. S. (2012). Understanding the pitfalls of CCS cost estimates. *International Journal of Greenhouse Gas Control*, *10*, 181–190. https://doi.org/10.1016/J.IJGGC.2012.06.004

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, *40*, 378–400. https://doi.org/10.1016/J.IJGGC.2015.05.018

Sanchez, N., & Mays, D. C. (2015). Effect of methane leakage on the greenhouse gas footprint of electricity generation. *Climatic Change*, *133*(2), 169–178. https://doi.org/10.1007/s10584-015-1471-6

Sathre, R., Chester, M., Cain, J., & Masanet, E. (2012). A framework for environmental assessment of CO_2 capture and storage systems. *Energy*, *37*(1), 540–548. https://doi.org/10.1016/J.ENERGY.2011.10.050

Sathre, R., Masanet, E., Cain, J., & Chester, M. (2011). The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS Environmental Energy Technologies Division. In *The role of Life Cycle Assessment in identifying and reducing environmental impacts of CCS* (p. 10). Pittsburgh, PA, USA. Retrieved from https://www.osti.gov/servlets/purl/1016012

Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M., & Bovensmann, H. (2014). Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. *Earth's Future*, *2*(10), 2014EF000265. https://doi.org/10.1002/2014EF000265

Shimekit, B., & Mukhtar, H. (2012). *Natural Gas Purification Technologies – Major Advances for CO_2 Separation and Future Directions*. Retrieved from http://cdn.intechopen.com/pdfs/35293/InTech-Natural_gas_purification_technologies_major_advances_for_co$_2$_separation_and_future_directions.pdf

Singh, B., Strømman, A. H., & Hertwich, E. (2011). Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. *International Journal of Greenhouse Gas Control*, *5*(3), 457–466. https://doi.org/10.1016/J.IJGGC.2010.03.006

Songolzadeh, M., Soleimani, M., Takht Ravanchi, M., & Songolzadeh, R. (2014). Carbon dioxide separation from flue gases: a technological review emphasizing reduction in greenhouse gas emissions. *The Scientific World Journal*, *2014*.

Telsnig, T., Tomaschek, J., Özdemir, E. D., Bruchof, D., Fahl, U., & Eltrop, L. (2013). Assessment of selected CCS technologies in electricity and synthetic fuel production for CO_2 mitigation in South Africa. *Energy Policy*, *63*, 168–180. https://doi.org/10.1016/j.enpol.2013.08.038

UNFCCC (2009). "Copenhagen Accord", UNFCCC secretariat summary, December 2009; http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php

UNFCCC (*2015*). "The Paris Agreement", UNFCCC secretariat main page on the topic; http://unfccc.int/paris_agreement/items/9485.php

UNFCCC (2016). "NDC Registry", UNFCCC secretariat main page on the topic; http://unfccc.int/focus/ndc_registry/items/9433.php

van Vliet, O. P. R. R., Faaij, A. P. C. C., & Turkenburg, W. C. (2009). Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. *Energy Conversion and Management*, *50*(4), 855–876. https://doi.org/10.1016/j.enconman.2009.01.008

Wallquist L., L'Orange Seigo S., Visschers V.H.M., Siegrist M. (2012). “Public acceptance of CCS system elements: a conjoint measurement”, *Int. Journal of Greenhouse Gas Control*, *6*: 77–83.

Wolff, J. (2014). What lessons can hydraulic fracturing teach CCS about social acceptance? *Energy Procedia*, *63*, 7024–7042. https://doi.org/10.1016/J.EGYPRO.2014.11.736

Worden, J. R., Bloom, A. A., Pandey, S., Jiang, Z., Worden, H. M., Walker, T. W., … Röckmann, T. (2017). Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget. *Nature Communications*, *8*(1), 2227. https://doi.org/10.1038/s41467-017-02246-0

WRI, (2010). “Guidelines for community engagement in carbon dioxide capture, transport, and storage projects”, by Micah Ziegler and Sarah Forbes, World Resources Institute, Washington DC, November 2010

Zahasky, C., & Benson, S. M. (2016). Evaluation of hydraulic controls for leakage intervention in carbon storage reservoirs. *International Journal of Greenhouse Gas Control*, *47*, 86–100. https://doi.org/10.1016/J.IJGGC.2016.01.035

Zapp, P., Schreiber, A., Marx, J., Haines, M., Hake, J.-F., & Gale, J. (2012). Overall environmental impacts of CCS technologies—A life cycle approach. *International Journal of Greenhouse Gas Control*, *8*, 12–21. https://doi.org/10.1016/J.IJGGC.2012.01.014

APPENDICES

Appendix A: CCS Projects Examples

Project	State	Operate since	Unique Properties	Emissions captured	Obstacles	Use for EOR[a]
Power plant CCS projects						
SaskPower's Boundary Dam	Canada	2014	The world's first commercial-scale CCS plant applied to coal-fired power generation (retrofit)	90% from a 110 MW coal unit, and 15% of the power station's total emissions. Supposed to captured 1 million tons of CO_2 annually		
Kemper County	Mississippi, USA	2016	New power plant using pre-combustion	65% of emissions – around 3.5 million tons a year	The plant suspends coal gasification, due to low Natural Gas prices[b]	Yes
Petra Nova	Texas, USA	2017	The world's largest post-combustion CC project presently in operation (retrofit)	CCS will cut the plants emissions by 9%		Yes
Industrial sectors – steel, cement, chemicals, fertilizer, hydrogen, refining[c]						
Shell Quest	Canada	2015	The first CCS project to reduce emissions from oil sands processing			

Project	State	Operate since	Unique Properties	Emissions captured	Obstacles	Use for EOR[a]
Emirates Steel Industries	Abu Dhabi	2016	The world's first application of CCS to iron and steel production	Approximately 0.8 Mtpa of CO_2		Yes
Tomakomai CCS Demonstration Project	Japan	2016	Capture emissions from a H_2 production facility and injecte them into near-shore deep geologic formations	Processing CO_2 at a rate of at least 100,000 tonnes per annum		
Natural gas processing[d]						
Val Verde Natural Gas Plants	Texas, USA	1972	The first project using by-product CO_2 for EOR[e]	Total capture capacity of around 1.3 Mtpa		Yes
Shute Creek Gas Processing Facility	Wyoming, USA	1986 with expansion in 2010	The raw gas entering the facility contains about 65% CO_2	CO_2 production capacity of 7 Mtpa		Yes
Sleipner CO_2 Storage Project	Offshore Norway	1996	First project done for mitigation, and the first to store CO_2 in a deep saline storage reservoir (800-1,100 meters below sea level). First large-scale CCS project to become operational in Europe	Approximately 1 Mtpa of CO_2 is injected per year, and a total of 17 Mt throughout 20 years of activity		
Snøhvit CO_2 Storage Project (LNG plant)	Norway	2008	CCS was a condition of the license to operate the project. the CO_2 injected into a geological storage reservoir	Designed to capture 0.7 Mtpa of CO_2 when the facility is at full capacity		

Project	State	Operate since	Unique Properties	Emissions captured	Obstacles	Use for EOR[a]
Century Plant	Texas, USA	2010 and second stage at 2012	The largest CO_2 separation capacity in the world	Full CO_2 capture capacity is 8.4 Mtpa		Yes
Lost Cabin Gas Plant	Wyoming, USA	2013 (For much of the plant's history, the captured CO_2 was vented to the atmosphere)		Has an agreement for purchase approximately 0.9 Mtpa of CO_2		Yes
Petrobras Lula Oil Field CCS Project	Offshore Brazil	2013	Deepest CO_2 injection well in operation	Approximately 0.7 Mtpa of CO_2 can be re-injected		Yes
Uthmaniyah CO_2 EOR Demonstration Project	Saudi Arabia	2015	EOR is not likely to be required at production scale for decades to come. However, the project has been developed to gain experience with this technique	Around 0.8 Mtpa will be injected for three to five years		Yes
Gorgon Project	Offshore Western Australian	2016	The largest in the world to inject CO_2 into a deep saline formation	Being capable of injecting up to 4 Mtpa of CO_2		
Salah	Algeria	2004	CO_2 storage in a saline aquifer	3.5 million tonnes had been stored	Capture was suspended in 2011 as there had been concerns about possible leakage	

---

[a] EOR has been a major driver of many early CCS projects, providing a revenue stream for the captured CO_2. In the United States, CO_2 has been used for EOR for several decades, facilitated by an existing network of CO_2 transport pipelines which span more than 6,600 km. In North America and in the Middle East in particular, there is potential to expand the use of EOR for climate change purposes by combining it with permanent CO_2 storage. This requires that EOR projects implement measures to verify that the CO_2 remains underground.

[b] In regions with low gas prices, such as the United States, advancing CCS on gas-fired power might be more favorable than for coal. At the same time, CCS on coal-fired power may turn out to be particularly attractive in the Asian market, including substantial retrofitting opportunities in China.

[c] Other projects include: Alberta Carbon Trunk Line, Alberta, Canada; Enid Fertilizer, Oklahoma, US; Illinois Industrial CCS Project, Illinois, US; Coffeyville Gasification Plant, Kansas, US; Great Plains Synfuel and Weyburn Midale project, North Dakota/Saskatchewan, US/Canada; Air Products Steam Methane Reformer, Texas, US.

[d] Excess CO_2 content in natural gas streams is a candidate for early CCS deployment, as the CO_2 must be separated from the gas before it can be sold. Gas suitable for use or 'sales' gas is composed almost entirely of CH_4, which is extracted from the natural gas through a series of processes. In addition to CH_4, raw natural gas can contain a range of other substances including water, petroleum fluids, CO_2, nitrogen, sulphur compounds, and other hydrocarbon gases such as propane and butane (which constitute liquefied petroleum gas or LPG).

Natural gas processing plants use a range of different processes to remove these various impurities and produce pipeline quality dry natural gas. Some of these substances, such as hydrocarbon liquids, LPG and sulphur, have commercial value and can be sold separately. Others, such as water and nitrogen, usually have no value and are re-injected into the gas reservoir or released. CO_2, as well, can be stored rather than being vented into the atmosphere.

[e] In any given reservoir, the amount of CO_2 co-produced with oil will increase with time; but the recycling systems employed at sites ensure that the vast majority of this CO_2 is reinjected into the reservoir in a closed loop system. EOR sites are designed to optimize oil recovery and minimize CO_2 purchases, so the storage resulting from EOR is often termed *associated* or *incidental.*

Appendix B: Currencies conversions

- For (**Folger, 2013**): 1 USD07 = 1*1.16*3.85 = 4.47 ILS_{16}. Using mid-year consumer price index (CPI) for United States Dollar, we get USD_{07}/USD_{16}= 1.16 (“Consumer Price Index Data from 1913 to 2017 | US Inflation Calculator,” 2017, “CPI Inflation Calculator,” 2017). Mid 2016 (29.6.2016), ILS_{16}/USD_{16}= 3.85 (“US Dollar (USD) To Israeli New Shekel (ILS) History - Foreign Currency Exchange Rates and Currency Converter Calculator,” n.d.).
- For (Finkenrath, 2011; Muratori et al., 2017): 1 USD_{10} = 4.27 ILS_{16}. Using mid-year consumer price index (CPI) for United States Dollar, we get USD_{10}/USD_{16}= 1.11 (“Consumer Price Index Data from 1913 to 2017 | US Inflation Calculator,” 2017; “CPI Inflation Calculator,” 2017). Mid 2016 (29.6.2016), ILS_{16}/USD_{16}= 3.85 (“US Dollar(USD) To Israeli New Sheqel(ILS) History - Foreign Currency Exchange Rates and Currency Converter Calculator,” n.d.). So, 1 USD_{10} = 1*1.11*3.85= 4.27 ILS_{16}.
- For (**Im et al., 2015**; **Rubin et al., 2015**): 1 USD_{13} = 3.97 ILS_{16}. Using mid-year consumer price index (CPI) for United States Dollar, we get USD_{13}/USD_{16}= 1.03 (“Consumer Price Index Data from 1913 to 2017 | US Inflation Calculator,” 2017; “CPI Inflation Calculator,” 2017). Mid 2016 (29.6.2016), ILS_{16}/USD_{16}= 3.85 (“US Dollar(USD) To Israeli New Sheqel(ILS) History - Foreign Currency Exchange Rates and Currency Converter Calculator,” n.d.). So, 1 USD_{13} = 1*1.03*3.85 = 3.97 ILS_{16}.
- For (**Chapman et al., 2013**): 1 GBP_{12} = 5.70 ILS_{16}. Using mid-year consumer price index (CPI) for Great Britain Pound, we get GBP_{12}/GBP_{16}= 1.10 (“Historical UK inflation rates and calculator,” 2018). Mid 2016 (29.6.2016) ILS_{16}/GBP_{16}= 5.18 (“XE: GBP / ILS Currency Chart. British Pound to Israeli Shekel Rates,” 2018). So, 1 GBP_{12} = 1*1.10*5.18 = 5.70 ILS_{16}.
- For (**Collodi et al., 2017**): 1 EUR_{14} = 4.32 ILS_{16}. Using consumer price index (CPI) for Euro (4Q2014, mid-year for 2016), we get EUR_{14}/EUR_{16}= 1.01 (“Euro Area Inflation Calculators,” 2018). Mid 2016 (29.6.2016) ILS_{16}/EUR_{16}= 4.28 (“Euro (EUR) and Israeli new shekel (ILS) Year 2016 Exchange Rate History. National Bank of Austria (NBA),” 2018). So, 1 EUR_{14} = 1*1.01*4.28 = 4.32 ILS_{16}.
- For (**Telsnig et al., 2013**): 1 ZAR_{07} = 0.45 ILS_{16}. Using mid-year consumer price index (CPI) for South African Rand, we get ZAR_{07}/ZAR_{16}= 1.72 (*South African Rand (ZAR)- CPI History*, 2017). Mid 2016 (29.6.2016), ZAR_{16}/ILS_{16} = 0.26 (“XE: ZAR / ILS Currency Chart. South African Rand to Israeli Shekel Rates,” 2017). So, 1 ZAR_{07} = 1*1.72*0.26 = 0.45 ILS_{16}.
- For (**Jaramillo et al., 2008**): 1 USD_{08} = 4.35 ILS_{16}. Using consumer price index (CPI) for USD (March 2008, mid-year for 2016), we get USD_{08}/USD_{16}= 1.13 (“Consumer Price Index Data from 1913 to 2017 | US Inflation Calculator,” 2017). Mid 2016 (29.6.2016), ILS_{16}/USD_{16}= 3.85 (“US Dollar(USD) To Israeli New Sheqel(ILS) History - Foreign Currency Exchange Rates and Currency Converter Calculator,” n.d.). So, 1 USD_{08} = 1*1.13*3.85 = 4.35 ILS_{16}.

References – Appendix B:

Consumer Price Index Data from 1913 to 2017 | US Inflation Calculator. (2017). Retrieved January 10, 2018, from http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/

CPI Inflation Calculator. (2017). Retrieved January 10, 2018, from https://www.bls.gov/data/inflation_calculator.htm

Euro (EUR) and Israeli new shekel (ILS) Year 2016 Exchange Rate History. National Bank of Austria (NBA). (2018). Retrieved January 11, 2018, from https://freecurrencyrates.com/en/exchange-rate-history/EUR-ILS/2016/oenb

Euro Area Inflation Calculators. (2018). Retrieved January 11, 2018, from https://www.statbureau.org/en/eurozone/inflation-calculators?dateBack=2014-12-1&dateTo=2016-6-1&amount=1000

Historical UK inflation rates and calculator. (2018). Retrieved January 10, 2018, from http://inflation.iamkate.com/

South African Rand (ZAR)- CPI History. (2017). Pretoria. Retrieved from http://www.statssa.gov.za/publications/P0141/CPIHistory.pdf?

US Dollar (USD) To Israeli New Shekel (ILS) History - Foreign Currency Exchange Rates and Currency Converter Calculator. (n.d.). Retrieved October 5, 2017, from http://usd.fx-exchange.com/ils/exchange-rates-history.html

XE: GBP / ILS Currency Chart. British Pound to Israeli Shekel Rates. (2018). Retrieved January 10, 2018, from http://www.xe.com/currencycharts/?from=GBP&to=ILS&view=10Y

XE: ZAR / ILS Currency Chart. South African Rand to Israeli Shekel Rates. (2017). Retrieved November 22, 2017, from http://www.xe.com/currencycharts/?from=ZAR&to=ILS&view=5Y

Appendix C: Post combustion CCS in NGCC power plants with original currencies

This data is available with ILS$_{16}$ values in Table 3-4.

Reference	IEA **(Finkenrath, 2011)**	UK CCS Task Force **(Chapman et al., 2013)**	CRS **(Folger, 2013)**	Rubin et al. **(2015)**	Muratori et al. (2017) Data is calculated for year 2020
Currency	2010 USD	2012 UK	2007 USD	2013 USD	2010 USD
Regular NGCC (no CCS)					
Net efficiency %	57%	54%	50%	51%	52%
Emission rate (tCO_2/MWh)				0.36	
Capital cost (cost/kW)	960$	550£		1049$	1050$
COE (cost/MWh)	77$	65.8£	65$	64$	-
NGCC with carbon capture only					
Emission rate (tCO_2/MWh)				0.04	
CO_2 reduction per MWh (%)				88%	
Net efficiency (%)	48%	45%*	43%	44%	42%
Relative decrease in net efficiency	15%	19%	16%	16%	24%
CO_2 captured (tCO_2/MWh)	0.362*			0.36-0.39	
CO_2 avoided (ton/MWh)	0.315	0.315*	0.315*	0.31-0.33	
Capital cost (cost/kW)	1715$	1351£*		2061$	2100$
Relative increase in capital cost	82%	145%*		96%	100%
COE (cost/MWh)	102$	103.4£	88$*	92$	-
Relative increase in COE	33%	57%	35%*	45%	-

Reference	IEA **(Finkenrath, 2011)**	UK CCS Task Force **(Chapman et al., 2013)**	CRS **(Folger, 2013)**	Rubin et al. **(2015)**	Muratori et al. (2017) Data is calculated for year 2020
Cost of CO_2 captured (cost/tCO_2)	80$	100£*	63$*	74$	91$
Cost of CO_2 avoided (cost/tCO_2)		119£*	73$*	87$	33$
Percentage of capture cost out of all CCS costs		70%*	80-90%		
NGCC with full CCS[25]					
COE (cost/MWh)	-	144£	92$	63-122$	-
Relative increase in COE	-	119%*	41%*	28-72%	-
Cost CO_2 avoided / tCO_2	-	248£*	86$*	59-143$	-

All data as appears in the articles, except when marked otherwise.
* Calculated from the article's data.

---

[25] The transportation and storage parameters are different in every article, therefor the results are more variable.

Appendix D: Calculation of CO_2e emissions during MeOH production

As calculated in the beginning of Chapter 3, the transportation fuel market size is expected to be at around 8 Mt gasoline equivalents/year. This means, a MeOH portion of 0.8 Mt gasoline equivalents/year. The density of gasoline is 0.75 kg/liter. Therefore, in 0.8 Mt gasoline we have 1.07 billion liters:

0.8 Mt / 0.75 kg/liter = 1.07 billion liters.

1 MeOH liter has 49% of the energy as in 1 gasoline liter. So, we need twice as much MeOH volume as that of gasoline, to drive the same distance. Therefore, 10% of all transportation fuels in 2030 equals 2.14 billion liters of MeOH.

Methanol density is 0.79 kg/liter.

2.14 billion liters * 0.79 kg/liter = 1.69 Mt MeOH.

0.8 Mt gasoline equivalents = 1.69 Mt MeOH.

We need 1.7 Mt MeOH/year to replace 10% of the transportation fuels mix in 2030.

Producing 1.7 Mt MeOH per year requires a MeOH plant that produces ~5,000 tMeOH/day:

1.7 Mt/year / 365 days = 4,631 tMeOH/day.

Average annual CO_2e emissions at the plant are 0.3-0.4 tons CO_2e/tMeOH (Collodi et al., 2017). Therefore, 1.7 Mt MeOH/year will emit 0.5-0.7 Mt CO_2e/year. Half of this emission, 0.25-35 Mt CO_2e, can be captured and utilized in the MeOH plants themselves, to boost MeOH production by up to 20%, without an increase in MeOH cost. This means that CCU in a MeOH plant can reduce its annual natural gas consumption by 20% while producing the same amount of MeOH, without an additional cost, and maybe even with profit (Collodi et al., 2017).

The other half of the CO_2e emissions (0.25-0.35 Mt CO_2e), that cannot be utilized in the MeOH plant, could be transported and stored without an increase in MeOH cost.

References – Appendix D:

Collodi, G., Azzaro, G., Ferrari, N., & Santos, S. (2017). Demonstrating Large Scale Industrial CCS through CCU – A Case Study for Methanol Production. Energy Procedia, 114, 122–138. https://doi.org/10.1016/j.egypro.2017.03.1155

Appendix E: Calculation of CO_2e emissions during GTL production

Using (Ou et al., 2013), we can calculate GTL gasoline CO_2e emissions per liter. The authors assume private car driving range of 100 km/6 liter of gasoline, and 100 km/4.8 liter of diesel at year ~2025. This equals to 16.6 km/1 liter of gasoline, and 21 km/1 liter of diesel. Life cycle assessment of GHGs emissions for GTL use are 215 g CO_2e/km.

16.6 km/liter * 215 g CO_2e/km = 3,569 g CO_2e/liter = 3.57 kg CO_2e/liter GTL gasoline.

Therefore, 1 liter of GTL gasoline emits 3.57 kg CO_2e through its life-cycle. (Jaramillo et al., 2008) gives a similar value: 3.45 kg CO_2e/liter domestic GTL gasoline. We will use ~3.5 kg CO_2e/liter GTL gasoline. For domestic GTL diesel, the value is 3.85 kg CO_2e/liter (Jaramillo et al., 2008).

1 liter gasoline weighs 0.75 kg, and 1 liter diesel weights ~0.85 kg. Therefore, 1 kg of GTL gasoline contains 1 liter/0.75 kg = 1.33 liter/kg; and 1 kg of GTL diesel contains 1 liter/0.85 kg = 1.18 liter/kg.

So, 1 kg of domestic GTL **gasoline** life cycle emissions are:

1.33 liter/kg GTL * 3.45 kg CO_2e/liter = 4.59 kg CO_2e/kg domestic GTL gasoline.

And, 1 kg of domestic GTL **diesel** life cycle emissions are:

1.18 liter/kg GTL * 3.85 kg CO_2e/liter = 4.54 kg CO_2e/kg domestic GTL diesel.

So, we will use an emission rate of 4.57 kg CO_2e/kg domestic GTL (gasoline or diesel).

Annual 0.964 Mt GTL = 0.964 * 1,000,000 * 1,000 kg GTL = $0.964*10^9$ kg GTL

$0.964*10^9$ kg GTL * 4.57 kg CO_2e/kg GTL = $4.41*10^9$ kg GTL = 4.41 MtCO_2e.

So, annual 0.964 Mt GTL in 2030, will emit 4.41 MtCO_2e.

CCS can reduce GTL life cycle emissions from 215 to 135 g CO_2e/km = 37% (Ou et al., 2013). So:

0.37 * 4.41 MtCO_2e = 1.63 MtCO_2e.

References – Appendix E:

Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2008). Comparative Analysis of the Production Costs and Life-Cycle GHG Emissions of FT Liquid Fuels from Coal and Natural Gas. *Environmental Science & Technology*, *42*(20), 7559–7565. https://doi.org/10.1021/es8002074

Ou, X., Zhang, X. X., Zhang, X. X., & Zhang, Q. (2013). Life Cycle GHG of NG-Based Fuel and Electric Vehicle in China. *Energies*, *6*(5), 2644–2662. https://doi.org/10.3390/en6052644

Environment & Energy

Samuel Neaman Institute
for National Policy Research

Tel. 972-4-8292329 | Fax. 97-4-8231889
Technion City, Haifa 3200003, Israel
www.neaman.org.il