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Philip Ringrose

How to Store CO_2 Underground: Insights from early-mover CCS Projects

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Foreword

Carbon dioxide capture and storage (CCS) is a crucial greenhouse gas mitigation technology. Not only can it decarbonise electricity generation from fossil fuels, where we also have other options, but it can decarbonise industrial sectors where there is no other low-carbon alternative, such as iron and steel production, cement production, refineries and other chemical industries. Even more than that, it can scrub carbon dioxide from the atmosphere, a 'negative emission' technology. These ideas are what lies behind the many analyses and scenarios developed by the International Energy Agency and the Intergovernmental Panel on Climate Change (IPCC) showing that we really need this CCS technology to achieve the 2-degree goal and even more vital for achieving the 1.5 degree ambition. Without CCS, these objectives are likely impossible to meet, and if achieved then at a much higher cost (e.g. 138% higher).

So, it gives me great pleasure in writing a recommendation for this book because it brings together two very important aspects—theory of CO_2 geological storage and learnings from real projects. The theory comes from what has been researched, modelled, published and taught at NTNU and other universities. But the theory only takes us so far. The gems are the learnings from real experience in the field, with suitable reflection and analysis to test theories and to extract further understandings and improve further the theory. Another key aspect is the transfer of this knowledge to others, especially students, who I am afraid to say will have to help deliver far more CCS than we have been able to do so far. In my role at IEAGHG, we try and assist the next CCS generation by running International CCS Summer Schools, we now have completed 13 and have some 600 alumni coming from over 49 countries. There is no question over the enthusiasm and capabilities of this next generation for this challenge. The author of this book has lectured and mentored at several IEAGHG Summer Schools, so I have seen first-hand how good he is at communicating these, at times complex, topics in a clear and easier-to-understand way to students from a wide spectrum of background. This book draws upon all of this. I recommend it.

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Acknowledgements

This short introduction to CO_2 storage could not have been possible without cooperation with numerous people—too many to mention. Industrial-scale projects, like the pioneering Sleipner CCS project, involve hundreds of engineers, technology specialists, managers and suppliers at each stage of the project. It has been my privilege to be a small part of such teams on a few of these projects. The experience I have gained working between the industrial and academic worlds has been especially valuable, and I wish to thank my colleagues, past and present, at Equinor (formerly Statoil), at the Norwegian University of Science and Technology (NTNU), at Heriot-Watt University and at the University of Edinburgh.

Where ever possible I have tried to attribute published sources, but some ideas just permeate. In writing this book, I have certainly borrowed concepts and ideas from colleagues without crediting them properly. So, I take this chance to give special thanks for the 'permeating of ideas and insights' which I know I gained from Anne-Kari Furre, Bamshad Nazarian, Gelein de Koeijer, Michael Drescher, Britta Paasch, Peter Zweigel, Allard Martinius and Guillaume Lescoffit (all at Equinor), Ola Eiken (Quad and Statoil), Martin Landrø (NTNU), Mark Bentley (Tracs and Heriot-Watt), Stuart Haszeldine (University of Edinburgh), Allan Mathieson (BP and Lloyd's Register), Gillian Pickup (Heriot-Watt), Sally Benson (Stanford University), Tip Meckel (BEG, Univ. Texas, Austin) and Tim Dixon (IEAGHG). Martin Landrø took the initiative to establish my position in CO_2 storage at the Norwegian University of Science and Technology, and together we started the first Bachelor/Master module on this topic in 2013. I would especially like to thank the first generations of students who asked tricky questions and helped identify things that are important to know and explain.

The CO_2 storage projects referred to in this book are biased towards Norwegian and European projects and Equinor's CCS operations—so I do apologise for neglecting important experience from elsewhere. Summarising complex topics can be tricky—so if I have over-simplified a topic that you know well, please be provoked to make things clearer for others, and feel free to disagree with my simplifications. Finally, I thank my family (Priscilla, Christy, Juliette, Miriam and

Daniel) for being patient with me for the time and energy I have devoted to CO_2 and rocks. There are other things in life that matter too—but climate and energy are pretty high on the list.

Contents

Nomenclature and Units

The SI International System of Units (Système Internationale d'Unités in French) is used through this book, often also referred to as the metric system of units. However, there are a few exceptions where non-SI units are used for convenience and following common practice:

- Rock unit permeability is usually given in millidarcy (mD). 1 darcy is approximately equal to 1 μm^2 (or 10^{-12} m^2) in SI units.
- Reservoir or well pressure is usually discussed in bars, where 1 bar = 10,0000 Pascals (Pa). Note the difference between bar_g (Gauge Pressure) and bar_a (Absolute Pressure), where bar_g is a reading relative to atmospheric pressure at the location, and bar_a is a pressure reading relative to an absolute vacuum.

A brief description of the main symbols used in this book is given in the table below.

A	Albedo
B_o	Bond number
B_{HC}	Hydrocarbon volume factor
C, C_o	Concentration, reference concentration
C_c	Capacity coefficient
C_a	Capillary number
c	Compressibility
Fm	Formation (stratigraphic)
g	Acceleration due to gravity (on Earth)
h	Height
k, k_r	Permeability, relative permeability
L	Length
P, p	Pressure
P_c	Capillary pressure
P_t	Threshold pressure
Q, q	Flow rate (volumetric)

R_f	Recovery factor
r	Radius
S	Saturation (also solar constant)
T, T_{eq}	Temperature, equilibrium temperature
t	Time
u_x	Flow velocity (in x-direction)
V	Volume
x,y	Horizontal coordinates
z	Vertical coordinate
α	Arrhenius constant
γ	Interfacial tension
Δ, δ	Difference in a property
∇	Gradient of a vector field
ε	Efficiency factor
θ	Angle
λ	Mobility
μ	Viscosity
ρ	Density
σ	Stress (or Stefan-Boltzmann constant)
ϕ	Porosity
Ψ	Ratio

Chapter 1
Why We Need Engineered Geological Storage of CO_2

1.1 Motivation

Reduction in global greenhouse gas emissions is a key issue for modern human civilization. Part of the solution to this challenge is long-term storage of CO_2 in deep geological rock formations. Other key solutions to achieving reductions in greenhouse gas emissions are to greatly expand the use of renewable sources of energy and to use energy much more efficiently. The main purpose of this book is to explain the concepts and technologies involved in the geological storage of CO_2. The material presented here was initially developed as course notes for the Masters' course module entitled 'Operation and Integrity of Engineered Geological Storage of CO_2' at the Norwegian University of Science and Technology (NTNU). The content has also proven useful in several short courses, such as the IEAGHG summer schools and industry courses for experienced professionals 'transferring into' CO_2 storage as a new emerging technology. As you will see this book offers only a short introduction to an extensive and multi-disciplinary topic, where detail and precision are important. However, the reader should not lose track of the essential message: that engineered geological storage of CO_2 is a relatively straightforward and established technology which will be urgently needed in the coming decades. Before digging into the topic of CO_2 storage, it is worth spending some time understanding why we need CO_2 capture and storage (CCS).

1.2 Brief History of Fossil Fuels

Since around 1800, humans have been rapidly increasing their consumption of fossil fuels, starting with coal during the industrial revolution, and then adding petroleum liquids and hydrocarbon gases leading to a significant increase in the rate of fossil-fuel consumption after 1950. This dramatic growth in the use of fossil fuel as an energy source has resulted in the consumption of a very significant fraction (roughly

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one third) of fossils fuel reserves, a resource which accumulated over 0.5 billion years of the Earth's history—coals and petroleum liquids having being derived from the remains of land plants and marine algae deposited and buried during a period of 540 Million Years (Ma).

Figure 1.1 shows historical data on global CO_2 emissions compared with some possible future trends. During the industrial and petroleum ages, human society became more and more dependent on increasing levels of fossil fuel combustion, resulting in an acceleration of CO_2 emissions to atmosphere. There is now widespread agreement that we need to change this behaviour—we must rapidly reduce this rate of CO_2 emissions to atmosphere. Over the last decade, despite many calls to reduce CO_2 emissions, all that has been achieved is a slowing in the rate of increase. The 2015 Paris agreement embodies the ambition to dramatically reduce emissions, with the goal of achieving "a balance between anthropogenic emissions by sources and removals by sinks in the second half of this century" (Paris Agreement, COP21, Article 4). To achieve this, a reduction in emissions of more than 50% is needed by 2050, with more detailed assessments of actions needed to avoid a global warming of 1.5 °C requiring pathways reaching around 80% reduction by 2050 (IPCC 2018).

Efforts to achieve this change in behaviour, with regard to greenhouse gas emissions, are generally summarized in terms of an 'energy transition' towards a set of low-carbon or 'green' forms of energy. The most widely accepted model for achieving this transition is the wedge model (Pacala and Socolow 2004), whereby gradual phasing in of renewable energy sources, adoption of energy efficiency measures and application of emissions reduction technologies for fossil fuels could enable this energy transition to occur within around 50 years. To achieve that transition, human societies will need to change their behavioural patterns and adopt new technologies for power generation, transport and industrial activities. At this point in time, most

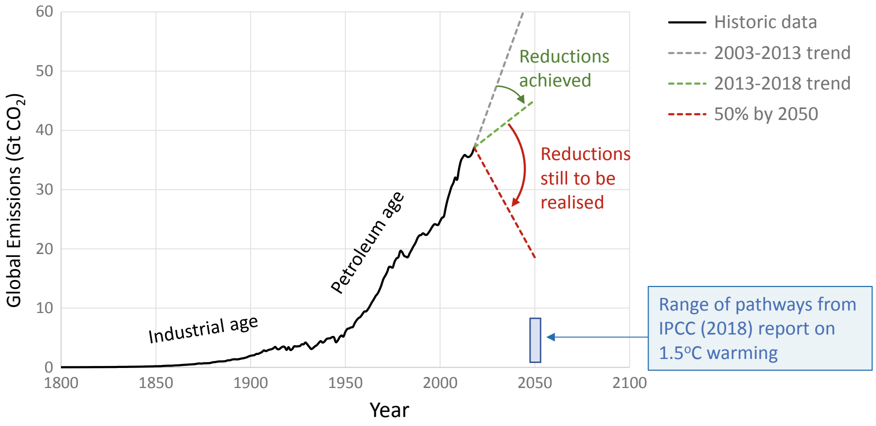

Fig. 1.1 Historical record of global CO_2 emissions compared with various projections (data sources: carbon emissions data up to 2013 from https://cdiac.ess-dive.lbl.gov/ with 2014–2018 years estimates from www.wri.org). Figure modified from Stephenson et al. (2019)