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Future of CO_2 Capture, Transport and Storage Projects

Analysis using a Systemic Risk Management Approach

Springer

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ISSN 2191-5547   ISSN 2191-5555 (electronic)
SpringerBriefs in Environmental Science
ISBN 978-3-319-74849-8   ISBN 978-3-319-74850-4 (eBook)
https://doi.org/10.1007/978-3-319-74850-4

Library of Congress Control Number: 2018930142

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface and Acknowledgements

The current book is an update of a Ph.D. thesis made in MINES ParisTech, from 2009 to 2012. The research question came up at that time is still topical. That is why we decided to readdress the question and analyze the evolution of the situation concerning Capture, Transport and Storage of CO_2 projects.

I wish to express my gratefulness to all the persons who made this possible, and especially my parents for their endless love and support.

Paris, France Jaleh Samadi

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Jaleh Samadi was awarded a Ph.D. in Engineering Science at MINES ParisTech, France. Since then, she has worked as Project Manager and Safety Engineer at EReIE (Energy Research, Innovation & Engineering) in France. She has been specially involved in the development and construction of an innovative biogas treatment/bioLNG production unit.

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Emmanuel Garbolino was awarded a Ph.D. in Geography at the University of Nice-Sophia Antipolis, and since 2002 has been a Lecturer and Assistant Professor at the CRC, MINES ParisTech.

Dr. Garbolino's research areas include climate change impacts on ecosystems and human societies, modeling of natural and anthropogenic systems, risk engineering dedicated to natural and anthropogenic hazards (risk assessment and prevention, crisis management, and damage assessment).

Dr. Garbolino is a member of the Education and Research Centre on CO_2 Capture, Transport and Storage.

Abbreviations

atm.	Atmosphere (pressure unit of measurement)
Ar	Argon
AS/NZS 4360: 2004	Australian/New Zealand risk management standard, version 2004
Bar	Pressure unit of measurement
BLEVE	Boiling Liquid Expanding Vapor Explosion
°C	Degrees of Celsius (temperature unit of measurement)
CCS	CO_2 Capture and Storage
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CTSC	Capture, Transport and Storage of CO_2
DNV	Det Norske Veritas
EIA	Environmental Impact Assessment
EOR	Enhanced Oil Recovery
ESD	Emergency Shut Down
EU	European Union
GCCSI	Global CO_2 Capture and Storage Institute
Gt	Giga (10^{12}) tonnes
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HSE	Health, Safety and Environment
ICPE	Installation Classée pour la Protection de l'Environnement
IEA	International Energy Agency
IEC 60300-3-9: 1995	International Electrotechnical Commission standard for risk management. Guide to risk analysis of technological systems, version 1995
IPCC	Intergovernmental Panel on Climate Change
IRGC	International Risk Governance Council

ISO/IEC 73: 2002	International standard for risk management—Vocabulary—Guidelines for use in standards, version 2002
km^2	Square kilometer
km	Kilometer
LNG	Liquified Natural Gas
LSIP	Large-Scale Integrated Project
m	Meter
max.	Maximum
MIT	Massachusetts Institute of Technology
Mtpa	Million tonnes per annum
N_2	Nitrogen
NGO	Non-governmental Organization
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
O_2	Oxygen
ppm	Parts per million
SO_2	Sulfur dioxide
STAMP	Systems-Theoretic Accident Model and Processes
STEL	Short-Term Exposure Limit
STPA	Systems-Theoretic Process Analysis
t	Tonnes
UK	United Kingdom
USA	United States of America

Introduction

Dear Reader,

Many thanks for choosing this book.

If you think that reading scientific works is usually boring, we are going to make it interesting together.

If you are ready, let's start our journey with some questions. The idea is to provide you with the key notions of this book and give you the desire to continue reading.

Don't worry, the answers are also provided to give you an initial idea about the subject of the book. If you are interested to know more about different topics, we invite you to have a look at the references at the end of each chapter.

Ready for the first question?

Let's go!

Question 1: Do you know what is **Climate Change**?

Answer 1: **Climate Change** is recognized as *an urgent and potentially irreversible threat to human societies and the planet* in the last conference on climate change held in Paris at the end of 2015 (COP21 2016).

Scientists believe that the temperature of the earth's surface is increasing, mainly because of anthropogenic greenhouse emissions, which have been growing exponentially since the beginning of the Industrial Age.

Question 2: What about the **certainty** of Climate Change?

Answer 2: Debates are still ongoing. But a number of scientific studies over the last decade **confirm the certainty** of happening climate change (Wennersten et al. 2015).

Question 3: What are the **commitments** of the latest international agreement on tackling Climate Change?

Answer 3: To meet the objectives of latest international agreement (COP21 2016), all countries should participate to reduce the global greenhouse gas emissions. The global temperature increase should be kept below 2 °C and efforts should be made to limit it to 1.5 °C.

Question 4: Is there any **method** to deal with Climate Change?

Answer 4: IPCC (Intergovernmental Panel on Climate Change) classifies the technical solutions to tackle Climate Change in two categories: mitigation and adaptation solutions (IPCC 2014). However, other classifications are also available. For example, Climate Control methods (such as CO_2 Capture, Transport and Storage or geoengineering), and alternative methods of energy production (such as nuclear and renewables) (Poumadère et al. 2011). These methods could be compared to the IPCC mitigation and adaptation solutions respectively.

Question 5: How we can choose the **most efficient method** to take action on Climate Change issues?

Answer 5: IPCC states that *neither mitigation nor adaptation alone can avoid climate change impacts* (Wennersten et al. 2015). So, there is not a single answer to this question. All solutions are welcome to make the objectives happen. A combination of solutions seems to be the most efficient.

Question 6: Will we talk about all different solutions in this book?

Answer 6: In this work, we put the emphasis on Capture, Transport and Storage of CO_2, as a mitigation solution to deal with Climate Change.

Question 7: What does "**Mitigation**" means?

Answer 7: *"**Mitigation**", in the context of climate change, is a human intervention to reduce the sources or enhance the sinks of greenhouse gases* (IPCC 2014). Capture, Transport and Storage of CO_2 (CTSC) is so considered as a mitigation technology.

Question 8: What is Capture, Transport and Storage of CO_2 (**CTSC**)?

Answer 8: **CTSC** consists of a chain of processes to collect or capture a CO_2 gas stream, transport the CO_2 to a storage location, and inject it into that location.

Question 9: How is **CO_2 emitted** into the atmosphere?

Answer 9: The most significant source of CO_2 emissions is the combustion of fossil fuels such as coal, oil and gas in power plants, automobiles, and industrial facilities. Chemical, metallurgical, and mineral transformation processes, agricultural activities, transportation, burning fuels for heat in buildings, or cooking in homes are some other sources of global greenhouse gas emissions (EPA 2016).

Question 10: What about the **concentration of CO_2** in the atmosphere?

Answer 10: CO_2 is the main greenhouse gas responsible for global warming. The current concentration of CO_2 in the atmosphere is now around 400 ppm (parts per million). Atmospheric CO_2 could reach 500 ppm by 2050 and 800 ppm by 2100 if current rates of greenhouse gas emissions continue (Wennersten et al. 2015). Figure 1 shows the evolution of CO_2 average concentration.

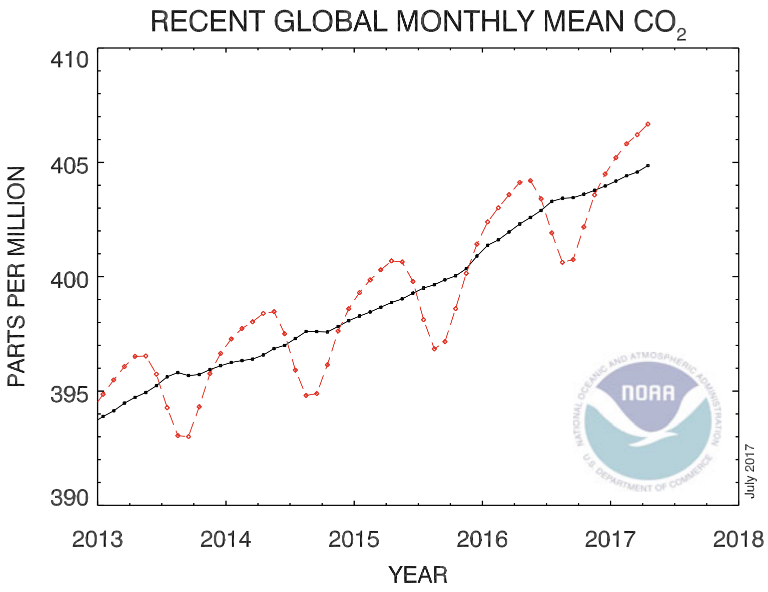

Fig. 1 Atmospheric CO_2 emissions evolution (ESRL 2017) Red line: Monthly mean values Black line: Monthly mean values, after correction for the average seasonal cycle

Question 11: Is there a global agreement about the **limit of CO_2 concentration** in the atmosphere?

Answer 11: There is not a general agreement about the "safe" limit of CO_2 concentration in the atmosphere. Staying under 350 ppm is just a figure which is noted in some scientific publications (Wennersten et al. 2015).

Question 12: **How much CO_2** has been already produced and emitted into the atmosphere?

Answer 12: In 2014, global CO_2 emissions reached 32.4 $GtCO_2$. No surprise, China (28%) and the United States (16%) are at the top of the list of emitting countries. CO_2 emission rate of top ten emitting countries in 2014—which produced two-thirds of global CO_2 emissions—is presented in Fig. 2.

Question 13: Does everyone have the **same idea** about the efficiency of CTSC technology in Climate Change tackling?

Answer 13: CTSC is still an unknown technology for many people even the stakeholders. Some other climate control or mitigation methods like geoengineering are also in the same case (Wennersten et al. 2015; Poumadère et al. 2011).

Perceptions of stakeholders on the effectiveness of CTSC are different. Although most of governments and industries intend to invest in the technology, others such as local communities and NGOs are worried.

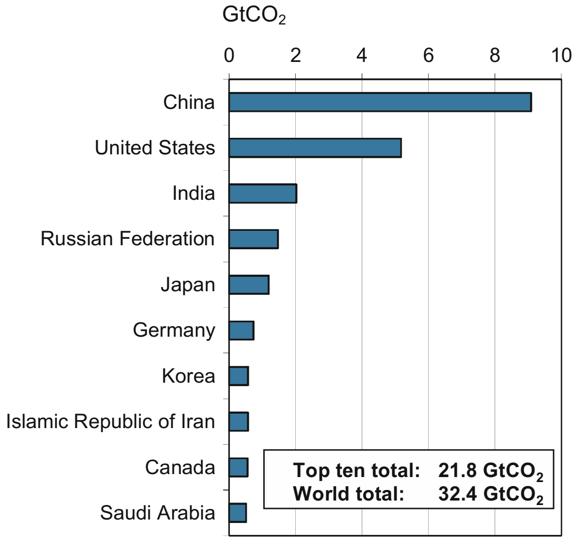

Fig. 2 Top ten emitting countries in 2014 (IEA 2016)

Question 14: What are the **concerns of the stakeholders** about CTSC technology development?

Answer 14: Stakeholders like local communities and NGOs are worried about long-term risks and reliability of CO_2 storage. CO_2 leakage is the most significant concern of these groups since it could lead to risks for human beings, animals, and plants as well as potable water networks.

Question 15: Is there any **solution** to help the stakeholders dealing with their concerns?

Answer 15: What we propose is a **development of adequate Risk Management methods** and use these methods from the very first phases of a CTSC unit development.

We believe that Risk Assessment and Management are essential parts of CTSC development in order to provide answers to the uncertainties and assure the control of well-understood parts of CTSC processes.

Experts' general opinion confirms that Risk Assessment is *vital for the success* of any CTSC project (Wennersten et al. 2015).

An efficient communication process is also required to exchange information about technical, economic feasibility, and social acceptance of the technology.

Question 16: Is there any **risk assessment method available** for CTSC?

Answer 16: Several studies have been carried out on risk assessment of Capture, Transport and Storage technologies. Risks of CO_2 Capture and Transport are supposed to be well understood. Therefore, classical methods have been usually applied for analyzing risks of Capture and Transport subsystems. However, CO_2

storage is known as a "*non-engineered*" part of the process, dealing with various uncertainties (Koornneef et al. 2012). Consequently, most of the available risk assessment studies are focused on CO_2 storage technical aspects of risk.

Question 17: How we can **improve** the available risk assessment methods?

Answer 17: What is neglected in most of the available approaches is that CTSC is a **complex sociotechnical system** for which risks could not be analyzed individually, without taking the whole context into account.

So, our proposition is to take this fact into account and study the whole system of risks associated with CTSC.

Question 18: What is a **Complex System**?

Answer 18: A Complex System is a *system composed of many parts that interact with and adapt to each other. In most cases, the behavior of such systems cannot be adequately understood by only studying their component parts. This is because the behavior of such systems arises through the interactions among those parts* (IRGC 2010).

Question 19: What is a **Sociotechnical System**?

Answer 19: A Sociotechnical System is a one which consists of a technical part which is in interaction with a social part.

Question 20: Is there any **major question about the development of CTSC** projects?

Answer 20: Risks associated with CTSC are not limited to technical risks. Along with technical challenges, CTSC is faced with uncertainties concerning development up to commercial scales. Seventeen large-scale CCS projects are currently in operation around the world (GCCSI 2017). In 2016, forty-three projects were announced canceled or on hold. Financial reasons are frequently noted as the reason for project failure. However, Public Opposition, Legal, Technical, and Policy concerns are some other reasons of projects' cancelation (MIT 2016).

Therefore, a major question about CTSC at the current scale of development is **what are the factors explaining the success or failure of CTSC projects in different contexts?**

Question 21: Any proposition for replying to the here-above question?

Answer 21: In order to answer this question, we propose **a systemic risk management framework** based on the concepts of System Dynamics and STAMP (Systems-Theoretic Accident Model and Processes), developed at Complex Systems Research Laboratory of Massachusetts Institute of Technology.

Question 22: Where does the idea of this book come from?

Answer 22: Aside from the sociotechnical complexity of CTSC system, the idea comes from **systemic and dynamic characteristics of risk**. Systems are regularly adapting themselves to perturbations. Nevertheless, positive feedbacks lead to system destabilization by amplifying the perturbations. So, it is important to identify feedback dynamics involved in the system in order to *better anticipate when risks might emerge or be amplified* (IRGC 2010).

In this book, systemic modeling is proposed as a decision-making support, which provides the grounds of thinking about the components of a potentially successful CTSC project. Each stakeholder is assumed as a "controller", who is responsible for maintaining safety constraints. Safety control structures are developed for several case studies to formalize the relations of stakeholders in maintaining safety constraints.

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