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ORIGINAL ARTICLE

Review of European energy policies regarding the recent "carbon capture, utilization and storage" technologies scenario and the role of coal seams

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Abstract European energy policy has made an effort in the last years in developing a coherent strategy towards the definition of a set of goals, involving the reduction in greenhouse gas emissions and, at the same time, increasing renewable energy use. This paper presents the different options of carbon capture, utilization and storage (CCUS) technologies regarding the legislative initiatives implemented in the new European energy policy. This new European energy strategy was established taking into consideration not only energy demand but also social and environmental requirements. Taking that into account, the different strategies adopted by the European energy council are discussed and an overview of carbon capture and storage (CCS) technologies—a mitigation strategy able to reduce greenhouse gas emissions—and the CO_2 potential utilization were also addressed. Conventional and unconventional CO_2 geological storage/sequestration reservoirs are analysed, taking into consideration the different properties of both types of reservoirs. Finally, it is possible to conclude that coal seams must play a major role in CCS/CCUS technologies, since coal is considered as an efficient technological solution to CO_2 geological storage/sequestration.

Keywords European energy policy · CCS technologies · CCUS technologies · CO_2 · Coal seam · Reservoir

Introduction

The beginning of the twenty-first century has been marked by new energy challenges, which are closely related to three major issues: the decline of conventional hydrocarbons reserves, i.e., oil and associated natural gas; the escalation of the external energy dependency; and the need to promote a sustainable global environment. Nevertheless, without underestimating the first two previously mentioned challenges, the external energy dependency appears as the major task to be solved in the new energy scenario. In fact, the need of a strategic vision and decision making, able to raise the energy supply, leads to the need of the diversification and replacement of existing resources and equipment and to providing infrastructures for and challenging energy requirements. It is also relevant to mention that these structural changes will have medium- and long-term consequences on the energy sector and consequently on society regarding medium- and long-term costs and security. In fact, due to the different problems we are dealing with today in the world, concerning not only the energy sector but also in terms of social and environment domains, the European Union has established five ambitious objectives:

1. Employment
2. R&D/innovation
3. Climate change/energy, to achieve the so-called "the three twenties"—reducing greenhouse gas emissions by 20 % (or perhaps 30 %, depending on the conditions), increasing renewable energies to 20 %, and increasing energy efficiency to 20 %

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4. Education
5. Poverty/social exclusion

European Energy policies are laid down in a central objective of ensuring the availability of energy products and services on the European market, at a viable price for all kind of consumers and taking into consideration social and climate special requisites. Based on this, the European Council has adopted ambitious energy and climate change goals for 2020, supported by two different, although complementary, initiatives:

- "The Energy 2020: a strategy for competitive, sustainable and secure energy" (European Commission 2010), and
- "Energy Roadmap 2050" (European Commission 2011b).

The first initiative, "The Energy 2020: A strategy for competitive, sustainable and secure energy", defined on the 10 November 2010 (European Commission 2010) has established the energy priorities for the next years and has set the actions to be taken in order to achieve the ambitious targets of reducing energy consumption, accomplishing a market with competitive costs and secure supplies, increasing technological leadership, developing infrastructures, and protecting consumers and increasing international cooperation. As a matter of fact, and as well known, the European external energy policy is essential to fully define the internal energy market. In fact, these priorities will probably help the European member states to create employment and assure productivity and social stability.

These goals are intended to be achieved through a series of legislative proposals unveiled by the European Council, such as:

- "Smart grids: from innovation to deployment" (12 April 2011) (European Commission 2011e), this proposal deals with the deployment of the future European electricity networks.
- "Directive on energy efficiency" (22 June 2011) (European Commission 2011c), the directive target resides on assisting European member states to develop strategies to use the energy more efficiently, from generation, transformation, distribution until consumption.
- "The EU energy policy: engaging with partners beyond our borders" (7 September 2011) (European Commission 2011a), this proposal intends to coordinate European external relations in energy.
- "Guidelines for trans-European energy infrastructure" (19 October 2011) (European Commission 2011d), the main objective of this proposal consists on guarantying that strategic energy networks and storage facilities are concluded until 2020.

The European energy strategy

The "European 2020" (European Commission 2007a) strategy established by the European Council in 2007 is currently improbable to achieve all the proposal targets, and it seems inappropriate to the longer-term tasks, established by the European Council, mainly in the energy field. In this context, the second initiative, "Energy Roadmap 2050" (European Commission 2011b), defined on 8 March 2011, was proposed to ensure security of energy supply and competitiveness and at the same time to explore routes to a low-carbon economy, intending to promote the decarbonisation of the energy system. The Europe is committed to achieve an 80–95 % reduction in greenhouse gas emissions by 2050, which will imply about 85 % decline of energy-related CO_2 emissions, including transport. This new energy scenario will also imply substantial modifications in different matters, such as carbon price, technology, and networks involved, which are supported by five priorities established by this new energy strategy:

- Achieving an energy efficient Europe;
- Building a truly pan-European integrated energy market;
- Empowering consumers and achieving the highest level of safety and security;
- Extending Europe's leadership in energy technology and innovation;
- Strengthening the external dimension of the EU energy market.

The gap identified in the "European 2020" strategy (European Commission 2007a), which makes this strategy inappropriate to achieve the European 2050 decarbonisation goal, proves the necessity for urgent and efficient actions aiming to achieve that goal. In this perspective, it is pertinent to highlight the fourth priority which was previously mentioned ("Extending Europe's leadership in energy technology and innovation") and specifically its number one action, i.e., to implement the European Strategic Energy Technology Plan (SET-Plan) (European Commission 2007b). This action has set the European Commission commitment to strengthen the implementation of the SET-Plan, especially the European energy research alliance (EERA) (available in http://www.eera-set.eu/), and the six European industrial initiatives: wind, solar, bioenergy, smart grids, nuclear fission, and carbon capture and storage (CCS). So, at this stage, it is clear that structural and social efforts must be put in both renewable and nuclear energies in order for them to become competitive and secure and consequently to be able to answer to the world's increasing energy demand. However, the promotion of a sustainable energy plan by the European Commission, which has been necessary due to the increasingly international energy demand, will still rely on the utilization of fossil fuel for power generation. In fact, fossil fuels will remain the dominant source of energy worldwide through at least two or three decades or even longer. In this perspective, and having full consciousness that it is pertinent to develop a fossil fuel strategic plan in an environmental sustainable basis, it is also well known that this difficulty can only be overcome by implementing the "zero-emissions technologies" (ZETs), such as clean coal technologies (CCTs) and the already mentioned CCS technologies. These technologies are the only ones able to meet the ambitious EU targets presented in the European Commission document entitled "limiting global climate change to 2 °C: the way ahead for 2020 and beyond" (European Commission 2007a), as well as, with the economic aspects of the EU Directives 2003/87/EC (European Commission 2003), and 2004/101/EC (European Commission 2004). The importance of this particular issue is well demonstrated with the European Commission formal admission that the referred targets will be impossible to reach without geological sequestration/storage. This is the reason why the European Parliament and the European Council proposed a European Union Directive on Geological Storage of CO_2, the so-called Directive 2009/31/EC unveiled in 23 April 2009 (European Commission 2009). This directive was established in order to define a regulatory framework for geological sequestration/storage of CO_2 regarding the conditions to deliver "storage permits" and promoting the respective envisioned of a global environmental integration. In fact, there is a need for the EU to be in reasonable balance with USA, Canada, and Australia in terms of Research and Technological Development (RTD) regarding CO_2 geological storage, in order to reduce fossil fuels industrial combustion emissions and at the same time to economically implement the corresponding technologies, i.e., competitively within the emissions allowance trading system of the EU Directives 2003/87/EC (European Commission 2003) and 2004/101/EC (European Commission 2004). In January 2014, the European Commission released a new document entitled "A policy framework for climate and energy in the period from 2020 to 2030" (European Commission 2014), which is perceived as an enforcement to the previous "Energy Roadmap 2050" initiative. This document aims to persuade the entities to work for a low-carbon economy and a competitive and secure energy system, able to ensure affordable energy for all consumers, which is supported by the following new mainstays: reduction in GHG emissions by 40 % below the 1990 level, implementation of renewable energy of at least 27 %, and new goals for energy efficiency energies and governance system.

CCS/CCUS technologies to address climate change

As an overview, it is now possible to accept CCS (IEA 2011; McCoy 2014) as a viable technological solution to reduce greenhouse gas emissions as a mitigation strategy on climate changes. The subject became so important that the European Commission commissioned a report to the European Academies Science Advisory Council (EASAC) on carbon capture and storage in Europe (EASAC 2013a, b). For that purpose, EASAC had established a working group in October 2011 to examine the challenges that should be addressed to secure CCS as a viable strategy to mitigate climate change, and consequently to consider what contribution it may make in Europe up to 2050 (EASAC 2013a, b). The full report on carbon capture and storage in Europe addresses the findings and recommendations of that mentioned EASAC study (EASAC 2013b).

Moreover, it is appropriate to mention the two totally different possibilities related to CO_2 abatement, which are biological fixation and geological sequestration/storage (Fig. 1). Yet, up to date, several studies have shown that biological fixation is technologically possible but economically unfeasible, due to different constraints mainly related to the flue gas produced from the industry which has high CO_2 concentration levels and toxic chemical compounds (SO_x and NO_x). Nevertheless, several geological solutions have been considered as technologically and economically feasible for CO_2 sequestration/storage, such as: (1) depleted oil and gas reservoirs, (2) deep saline aquifers, (3) coal seams, (4) shale gas, and (5) mineral carbonation (storage in mineral form in ultrabasic rocks).

The new CCS scenario, which implies the inevitability to address the global environmental challenge of climate change in a totally different and innovative perspective, requires a wide based strategy to ensure long-term sustainability (Barros et al. 2012; Lemos de Sousa et al. 2009). In this context, the Carbon Sequestration Leadership Forum (CSLF) (23 September 2011), available in http://www.cslforum.org/meetings/beijing2011/index.html has changed the term CCS to CCUS (carbon capture, utilization and storage) (CSLF 2011), supported by the perception that it is pertinent to promote demonstrations and deployment research projects to use, in addition to permanently store the emitted CO_2, which will help reducing human-generated CO_2. These CO_2 utilization pathways have been recently analysed and investigated in entirely different scenarios, as illustrated in Fig. 2, which leads to the achievement of two main goals: the reduction of atmospheric CO_2 emissions and the creation of new products, jobs, and profits.

However, the majority of the potential uses of CO_2 presented in Fig. 2 are presently implemented only at a small scale, resulting in no real net CO_2 reduction. On the

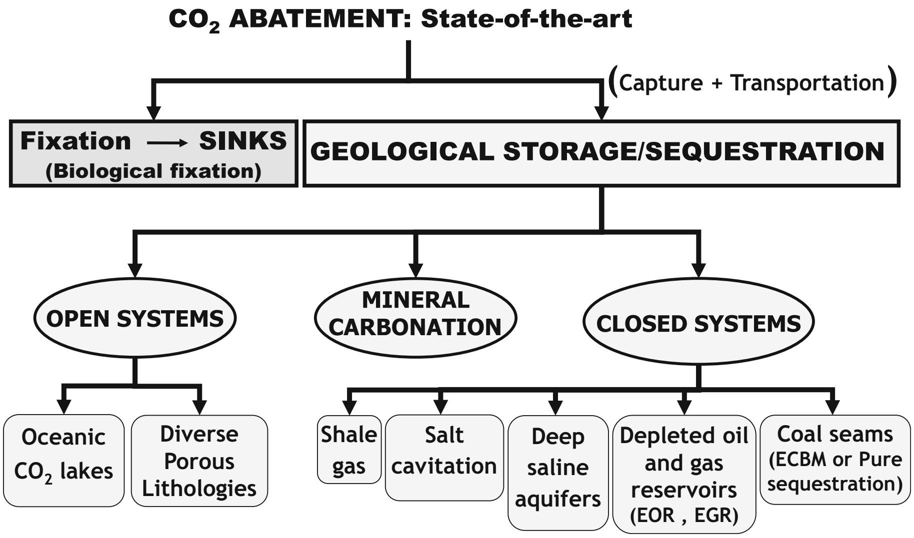


Fig. 1 CO_2 abatement: state of the art (Lemos de Sousa and Rodrigues 2008)

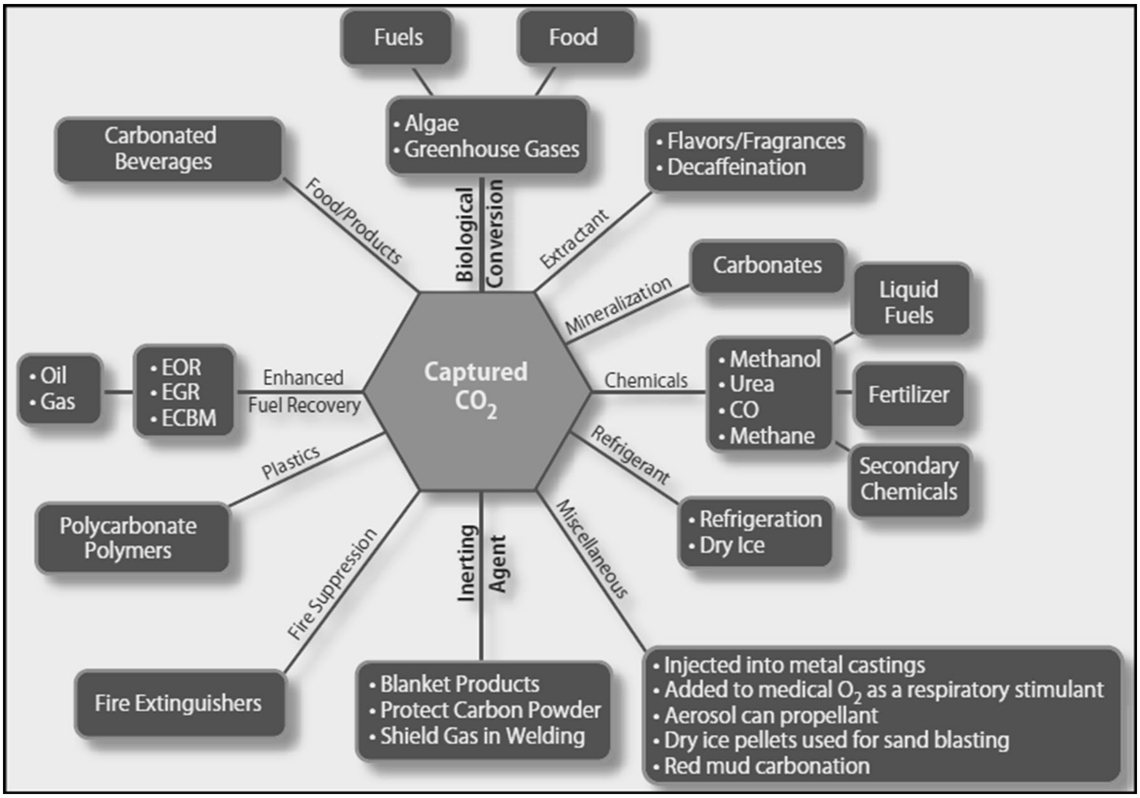


Fig. 2 Diagram showing the varied and plentiful current and potential uses of CO_2 CSLF (2011)

contrary, depleted oil and gas reservoirs (after production or during production, adding the benefit of helping to drain oil and gas from reservoirs, the so-called EOR/EGR), coal seams [abandoned mines or unminable deep seams are being used to produce enhanced coal bed methane (ECBM)], as well as shale gas technologies have already proven to be viable in terms of permanent CO_2 disposal and, at the same time, to allow the production of large quantities of oil and gas, able to be used as important energy sources.

Conventional versus unconventional reservoirs

It is appropriate, at this moment, to introduce two general concepts—“conventional reservoirs” and “unconventional reservoirs”, which are more suitably connected to the “closed systems” sector, earlier mentioned in Fig. 1. In fact, “salt cavitation,” “deep saline aquifers,” and “depleted oil and gas reservoirs” are classified as conventional reservoirs, while “coal seams” and “shale gas” fall into the unconventional reservoirs domain. This division between conventional and unconventional reservoirs is established taking into consideration their geological and petrophysical–chemical properties, which will induce distinctive CO_2 storage and circulation (flow) capacities. These properties are currently used as key parameters in the implementation of CCS/CCUS technologies, to promote the CO_2 storage security, in both healthcare and environmental domains, in short term (over a few decades of injection and storage monitoring) and on the long term (several hundred to thousands of years), in order to be established as a viable permanent solution. The distinctive performance of CO_2 storage and CO_2 circulation in both unconventional and conventional reservoirs, previously mentioned, is explained by the fact that in the former reservoirs, and mainly in the coal seams' case, the CO_2 is stored in the adsorbed and desorbed/free states and the CO_2 circulation obeys to two different processes, the diffusion and the laminar flow, respectively (Rodrigues et al. 2011, 2013); and in the second type of reservoirs, the CO_2 is stored in the absorbed/free states and, consequently, the circulation process is controlled by the laminar flow. Table 1 presents a comparison between some geological parameters of conventional and unconventional reservoirs, in which it is important to highlight the trap and the seal performances in the unconventional reservoirs. In fact, due to the high organic matter content characteristic of both coal seams and shale gas, the geological parameters, trap and seal, do not have a relevant role in the reservoir storage process, since in organic-rich reservoirs, the CO_2 entrapment is mainly achieved by the matrix of organic matter adsorption behaviour.

The role of coal seams in CCS/CCUS technologies

According to the European Commission (European Commission 2011b), all alternative solutions must be considered in order to reach the new energy targets. At this point, and taking into consideration the general geological parameters previously described, it seems obvious that coal seams may in fact and must actually play a major role in the CCS/CCUS technologies implementation. In fact, due to the high organic matter content presented by coal (ISO 11760 2005), which leads to a high CO_2 storage capacity in a permanent and secure way, coal has been considered as one of the best technological solutions for CO_2 geological sequestration/storage, despite some still existing constraints related to the diversity of coal quality identified in different regions and mines (Ansolabehere et al. 2007; Gentzis 2000; Metz et al. 2005a, b).

In this perspective, coal has been analysed and used in the last two decades as a natural gas and CO_2 reservoir, besides its traditional fossil fuel role, which allows it to be used as a product in power plants' combustion. Therefore, in this new reservoir scenario coal must be studied as a unique and highly heterogeneous sedimentary rock in its composition and structure, and this will induce two typical and distinct porosity systems at a large scale: the microporous structure (coal pores), and the cleat system (natural fracture network). These two distinct porosity systems are responsible for the different coal storage and circulation processes, already mentioned (Dinis 2010; Rodrigues 2002). The CO_2 storage within the microporous structure is performed by the adsorption process, which corresponds to over 95–98 % of the CO_2 storage, and the circulation is controlled by diffusion mechanisms (Dinis and Rodrigues 2010; Rodrigues and Lemos de Sousa 2006; Rodrigues et al. 2008). The absorption process is responsible for the rest (2–5 %) of the CO_2 storage, which occurs in the natural fractures network (Rodrigues et al. 2003, 2014), and the CO_2 circulation is conducted through the laminar flow.

Coal seam is in practice a porous medium reservoir characterized by a unique microstructure (Rodrigues and Lemos de Sousa 2002), which permits to store a CO_2 volume much higher than its pore volume capacity. In fact, due to coal adsorbed inherent characteristics, the CO_2 is heterogeneously stored in the pores structure; it means that CO_2 is mainly stored in the pore internal surface areas in a condensed form, which is very close to a liquid state. On the contrary, in conventional reservoirs, the CO_2 is homogeneously stored in the pore network, meaning that the stored CO_2 volume depends on the pore volume available in the reservoir. Therefore, it is possible to conclude that the coal porous structure must be analysed in a totally

Table 1 Characteristics of some important geological parameters in conventional and unconventional reservoirs (modified from Sahay and Van Dyke 2010)

Geological parameters	Conventional reservoirs (CR)	Unconventional reservoirs (UCR)
Trap	Present	Entrapment by adsorption in matrix of organic matter (trap not necessary)
Seal	Present	Entrapment by adsorption in matrix of organic matter (seal not necessary)
Reservoir porosity	High >10 %	Low <10 %
Reservoir permeability	High >100 mD	Low <0.1 mD

CR—depleted oil and gas reservoirs, deep saline aquifers, and salt cavitation. UCR—coal seams and shale gas different way from the porous structure of conventional reservoirs, since in the case of coal reservoir, smaller pores imply higher internal surface areas and consequently higher storage capacity, while in the case of conventional reservoirs, the higher storage capacity is achieved in reservoirs characterized by larger pores, which implies higher void volumes (Fig. 3). Moreover, in both cases (coal reservoir and conventional reservoirs), all the processes previously mentioned are entirely influenced by reservoir temperature and pressure conditions implying strong variations in CO_2 physical and chemical properties. Additionally, coal storage and circulation capacities are rather complex, largely beyond the simple measurement of the pore volume and understanding the condensed adsorption state and the diffusion process, since both storage and circulation processes also dependent on the pore size (consequently on the maceral composition, mineral matter content, and finally on the aromatization structure of coal, intimately related with its rank) and on the CO_2 purity of the gas.

The role of coal seams on the CCS/CCUS technologies implementation is obvious, when considering coal's inherent adsorption characteristics. Nevertheless, coal seams as a CO_2 reservoir present some constraints mainly related to the CO_2 injection phase. In fact, coal seams are usually characterized by low permeability values (Table 1), depending on their geological parameters, which implies the application of advanced technologies during the CO_2 injection procedure. Yet, this is one of the reasons that will ensure the permanent and secure CO_2 geological sequestration/storage in coal seams, which is one of the major requisites established in the European Directive 2009/31/EC. Another constraint must be considered whenever coal has been pointed out as CO_2 geological sequestration/storage solution. It means that it is important to study coal shrink and swelling effects, which will decrease with rank increase. In fact, these effects are almost minimized in high-rank coals, which put anthracites in a prominent position concerning the CO_2 geological sequestration/storage subject.

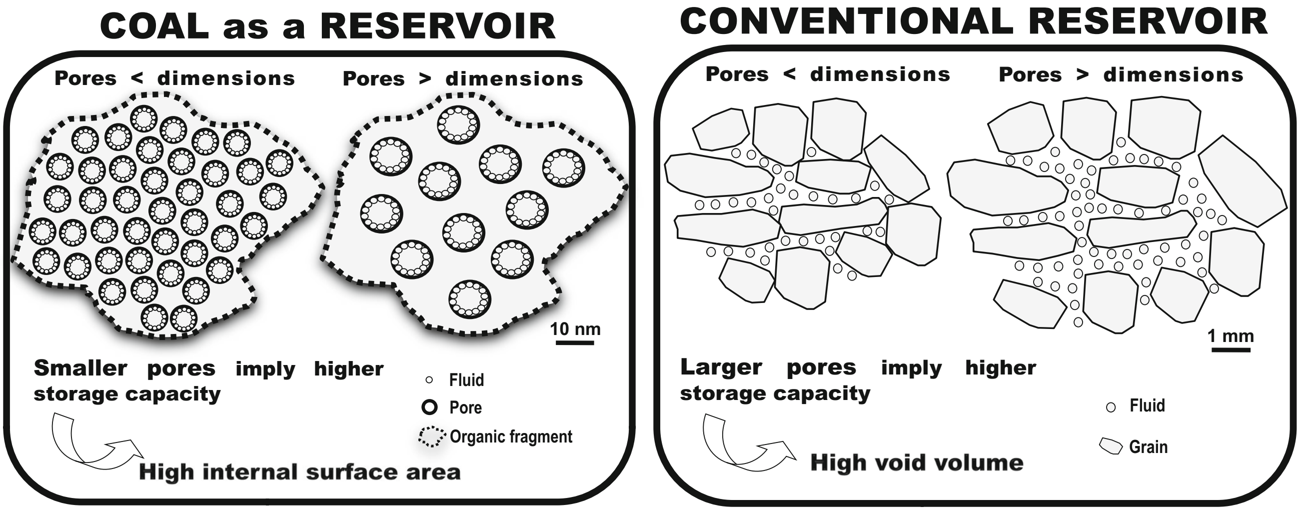
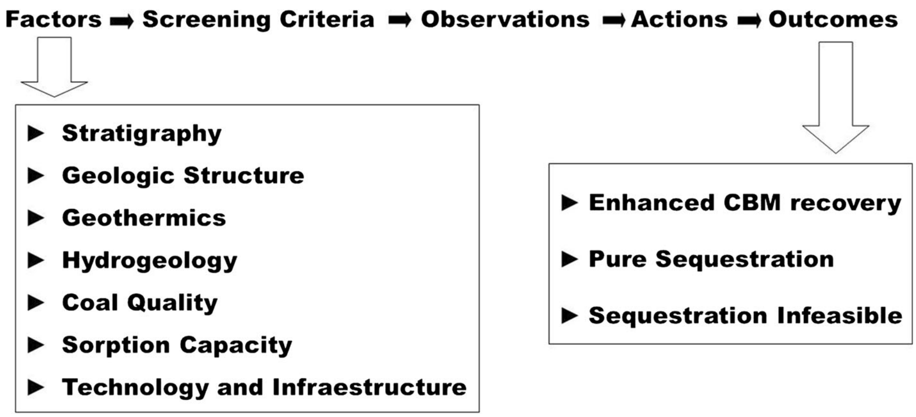


Fig. 3 Storage capacity of a coal reservoir (unconventional reservoir) versus a conventional reservoir (Rodrigues and Lemos de Sousa 2008)

Fig. 4 Screening criteria for CO_2 sequestration in coal seam reservoirs (Pashin et al. 2004)



However, to define the CO_2 storage capacity within a range of coal seams of diverse geologic origin and quite different petrological and physical characteristics, it is important to follow a screening criteria like the one proposed by Pashin et al. (2004) (Fig. 4). In fact, CO_2 permanent and secure storage in coal seams must be systematically assessed through modelling/simulation, taking into account standardized static and dynamic parameters. The screening criteria final goal consists on establishing guidelines to estimate the feasibility and efficiency of CO_2 storage in coal seams. The CO_2 storage feasibility and efficiency must be always performed in both technical (storage capacity potential and long-term risk assessment) and economic (capture and storage costs vs. carbon costs in the emissions allowance trading scheme) domains in order to allow different decisions regarding the abilities and limitations of CCS/CCUS technologies.

Conclusions

Sustainable energy is one of the challenging areas in the twenty-first century. Conventional hydrocarbon reserves are declining and a sustainable environment is being promoted at a worldwide scale. External energy dependency addresses major issues, and it needs to be overtaken through the use of other sources of energy. Within the several questions being focused, the European Union has designed several legislative initiatives aiming to create employment in this area, as well as guaranteeing productivity and social stability. Among other alternatives, renewable and nuclear energies emerge as solutions to answer to the rising energy demand, although fossil fuels will remain as the main source of energy available.

Carbon capture and storage (CCS) is actually accepted as a viable solution to reduce greenhouse gas emissions, now including the term “utilization” (CCUS), addressing the issue of CO_2 utilization pathways, involved in CO_2 storage. From that point of view, the comparative discussion of conventional and unconventional reservoirs is useful, since it allows understanding how coal seams are able to permanently and securely store CO_2 and positively contribute to CCS/CCUS technologies. Coal is a heterogeneous sedimentary rock and its unique composition and structure presents a very interesting alternative to CO_2 storage, since coal is able to store a CO_2 volume much higher than its pore volume capacity, as CO_2 in coal is mainly stored in the pores internal surface area and not in the empty pores space, and thus coal seams may effectively contribute to a European sustainable environmental energy policy.

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